Concawe
Environmental Science for European Refining

Review

Volume 29 • Number 1
June 2020

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Foreword

As the first 2020 edition of the Concawe *Review* is about to be published, it is reported in the news that this winter has been, until now, the warmest ever in EU countries, providing further evidence of climate change. In line with the European Green Deal and Europe's ambition to reach climate neutrality in 2050, Concawe continues to explore the contribution that the refining industry can bring to this objective. Two articles in this *Review* emanate from our Low Carbon Pathways programme.

The first article shows the potential for increased fuel economy that high-octane gasoline can bring to an optimised engine. Even if the potential for reducing greenhouse gas emissions is limited, no contribution should be overlooked if we want to achieve our target.

The European Green Deal also calls for a zero-pollution environment. The second article in this *Review* provides an overview of air quality in Europe and the potential improvements that would be achieved through different, very ambitious scenarios. This knowledge is important in the context of the fitness check on the Ambient Air Quality Directives launched by the EU Commission.

The third article summarises two important reports that have recently been published by Concawe, which investigate the different possibilities for European refineries to reduce the CO_2 emissions coming from their processes on the one hand, while on the other hand reducing the carbon content of the fuels produced, by differentiating the feedstocks and introducing new technologies.

Jean-Marc Sohier
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Contents

Concawe has previously undertaken and published the results of two studies aimed at understanding the relationship between octane and the performance and efficiency of mainstream Euro 4 to Euro 6 vehicles. While the performance and efficiency of these vehicles showed some small relationship to octane, it was important to note that most of these vehicles were not calibrated to take full advantage of fuels with a Research Octane Number (RON) in excess of 95.

To assess the full potential for higher octane fuels to lower vehicle CO_2 output and fuel consumption when measured over current legislative drive cycles, a test-bed and vehicle study was carried out using a highly downsized (30 bar BMEP), high-compression ratio (12.2:1) engine with a series of four fuels with RON numbers ranging from 95 to 102. This high compression ratio is higher than that of the baseline engine (10.2:1), and is enabled by the anti-knock properties of the high RON fuels.

Prior to measurement, the engine was calibrated specifically for each fuel over the full engine map. This ensured that the engine would experience the maximum benefit from changes in fuel properties. Based on the test-bed data, a GT-Drive model predicted the CO_2 emission and fuel consumption over the New European Drive Cycle (NEDC), the Worldwide harmonised Light-duty Test Cycle (WLTC) and multiple Real Driving Emissions (RDE) cycles of differing severity.

The engine was subsequently fitted to a D-segment vehicle and NEDC, WLTC and RDE cycles were performed to validate modelled efficiency improvements. These vehicle tests demonstrated:

- A fuel consumption benefit of up to 3.9% for the RON 102 fuel relative to the baseline 95 RON fuel in real driving conditions on the high compression ratio engine. Adding the benefit of the compression ratio increase from 10.2:1 to 12.2:1 allowed by the fuel's anti-knock behaviour, the fuel consumption benefit reaches up to ~5%;
- A linear improvement in the fuel consumption benefit between RON 95 and RON 102, meaning that each RON increase between these two values is beneficial to fuel consumption.

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This article presents results from a modelling study carried out to examine how annual average PM and NO_2 concentrations would vary under different emission reduction scenarios, and to assess the cost and the practicability of achieving compliance with the current EU air quality limit values (AQLVs).

The study highlights the fact that assessing how the risks associated with air pollutants should be managed is as important as quantifying the environmental and human health impacts. It is relevant to the ongoing fitness check of the Ambient Air Quality (AAQ) Directives launched by the European Commission in 2018 and the review process that would precede revision of the Directives and particularly the AQLVs therein.

The major findings of the study indicate the following:

- Under current legislation, $PM_{2.5}$ and NO_2 concentrations will reduce from 2025 onwards. However, full compliance with the existing EU AQLVs will not necessarily be achieved in all EU countries.
- Further emission reduction measures, beyond current legislation, will only have a small impact on the reduction of PM and NO_2 concentrations and compliance with AQLVs despite a substantial economic investment.
- In some countries (e.g. Poland for $PM_{2.5}$ and France for NO_2), full compliance with the current AQLVs remains unachievable even if all known abatement measures are applied.

Running high-octane petrol in a suitably adapted engine

Concawe's modelling and vehicle testing study shows that fuels and vehicles can be optimised together to take advantage of higher-RON fuels, and achieve significant improvements in efficiency and CO_2 emissions.

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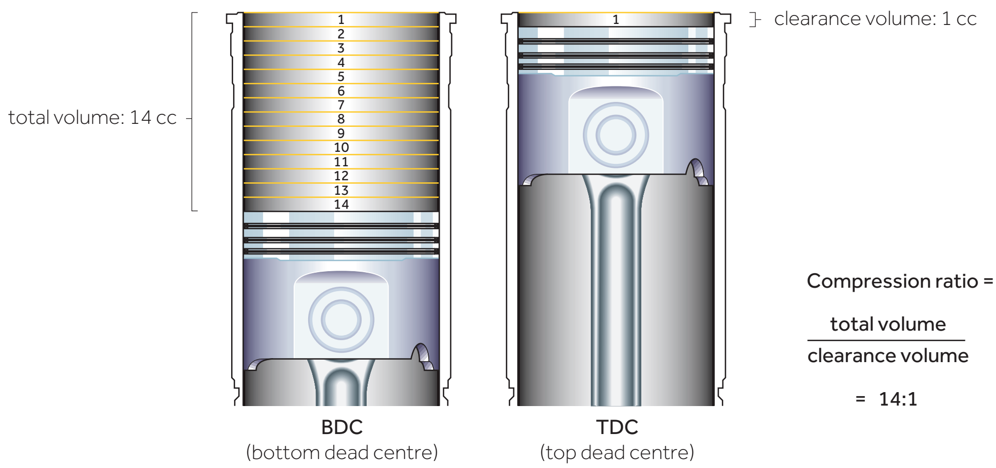
Background

Gasoline combustion has traditionally been measured using Research Octane Number (RON) and Motor Octane Number (MON) which describe the fuel's resistance to auto-ignition (commonly known as 'knock') under different conditions. All modern European gasoline cars must be capable of running on the regular 95 RON grade petrol. However, some vehicles are calibrated to be able to take advantage of higher-octane fuels available in the market, typically by advancing spark timing or increasing boost pressure, which can produce more power and, potentially, better fuel consumption. An article in the last edition of the Concawe *Review* discussed the possibility of producing higher-octane fuels from a refinery perspective using Concawe's refinery planning model.[1] The current article is the second in the series, and focuses on a modelling and vehicle testing programme conducted by Concawe to demonstrate improvements in fuel consumption for a range of higher-octane fuels in a specially adapted vehicle beyond the calibration aspects mentioned above.

In the future, gasoline engines with higher or variable compression ratios (VCRs) may be made available. While such engines are not commercially available at the present time, the concept is well-understood and demonstration engines exist.

Figure 1: Engine compression ratio — an example

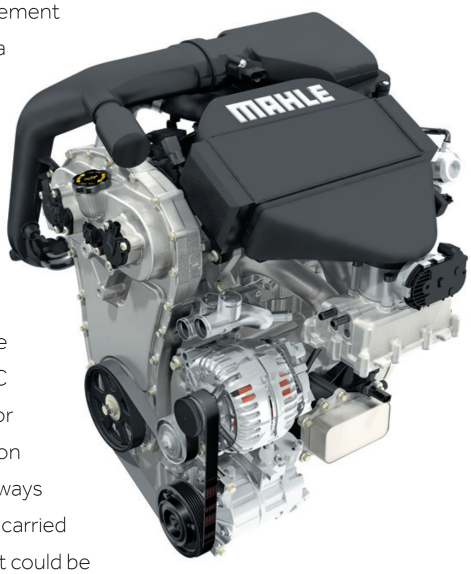


Compression ratio is calculated by dividing the total volume of the cylinder when the piston is at BDC by the clearance volume when the piston is at TDC. In the example on the right, the compression ratio would be expressed as 14:1.

The compression ratio (CR) is a measure of the compression of the air inside a vehicle piston, and is calculated by dividing the total volume of the cylinder when the engine piston is at bottom dead centre (BDC) by the volume when the piston is at the top of the stroke, i.e. at top dead centre (TDC). There are many studies in the literature which suggest that engines with higher compression ratios can take full advantage of improved thermal efficiency when run with higher-octane fuel, leading to improved fuel consumption. The downsized high-compression ratio engine used in this study was used in a previous study[2,3] and was loaned to Concawe for the programme by BP. The engine was a downsized version of a 2.0 litre engine, with a final swept volume of 1.2 litres and a compression ratio of 12.2:1 compared to that of the original engine, which was 10.2:1. The engine details are shown in Table 1 on page 5.

Table 1: Properties of the downsized high-compression engine used in the study

Number of cylinders	3
Capacity	1,199.5 cm^3
Bore	83 mm
Stroke	73.9 mm
Compression ratio	12.2:1
Maximum brake mean effective pressure (BMEP)	30 bar
Peak power	120 kW (at 5,000–6,000 rpm)
Peak torque	286 kW (at 1,600–3,500 rpm)



Left: the downsized high-compression ratio engine used in the study.

Image courtesy of MAHLE Powertrain

The results of the original BP work showed an improvement in efficiency of ~5% with a 102 RON fuel compared to a 95 RON fuel over a range of test cycles when the two compression ratios were also varied. BP's work showed that this improvement of ~5% was split into two parts: for example, in real driving conditions, a contribution of 4% was due to the RON increase while a contribution of 1.3% was due to the compression ratio increase. Interestingly, this work also showed that, when the driving conditions are less dynamic (typically the NEDC or WLTC), the RON's contribution decreases more or less as much as the compression ratio's contribution increases, so that the efficiency improvement is always ~5% whatever the driving cycle. The current study was carried out to gain a better understanding of the benefits that could be obtained with intermediate octane fuels in between the range that had been studied previously, using the same fuel formulations as those used in the aforementioned refining blending study (Concawe *Review*, Vol. 28, No. 1), i.e. 95, 98, 100 and 102 RON. A second goal of this study was to further validate these simulation results (based on engine test data) with a full vehicle demonstration.

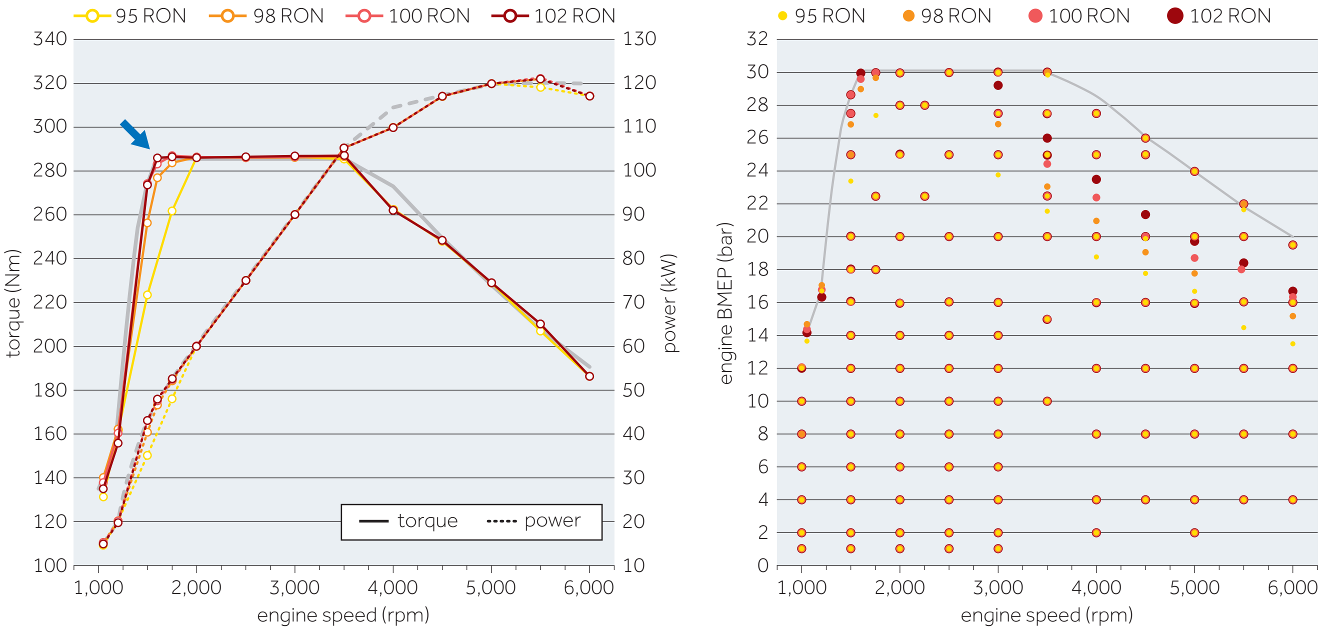
Engine testing and calibration

To ensure that the engine performs at its best with each fuel tested, it was calibrated for each fuel over the full range of speed and load points. The speed-load curves for all of the fuels are superimposed on Figure 2a, where load is expressed in terms of torque, from which it can be seen that the fuels are well matched. Figure 2b shows the speed-load points measured for each of the fuels, where load is expressed in terms of BMEP; these were kept the same wherever possible, except when fuel differences did not allow for this.

Figure 2: Speed-load curves and measured points for each of the fuels tested

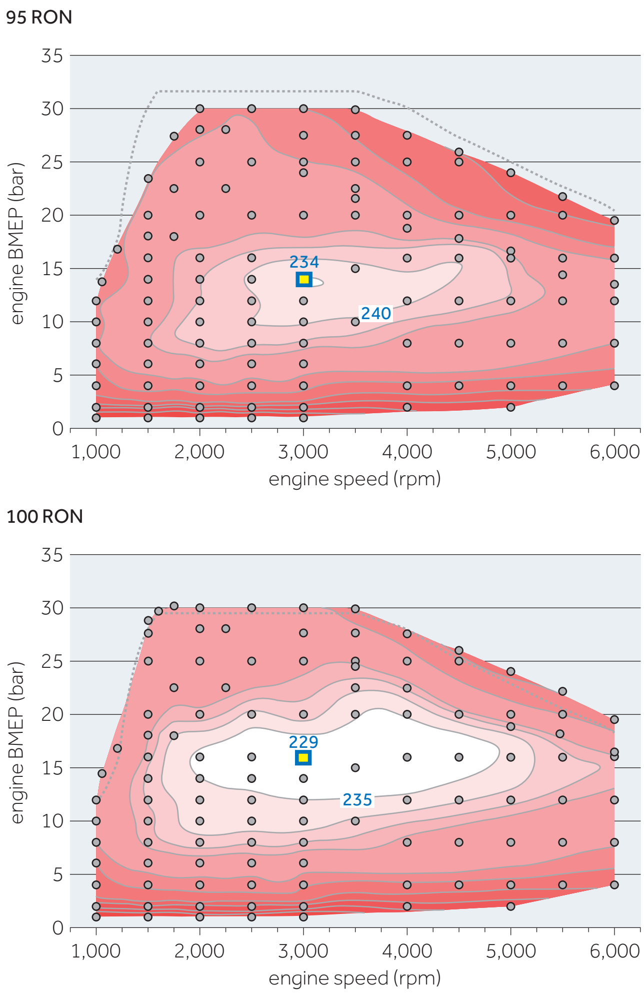
a) Speed-load curves

b) Measured speed-BMEP points



The main goal of the study was to understand the effect of octane on fuel efficiency. The contour plots shown in Figure 3 demonstrate the benefits. In this figure, the iso-contours represent the iso-BSFC (brake specific fuel consumption, expressed in g/kWh) areas. The darker tints on the figure indicate poorer efficiency (higher BSFC) and the lighter tints better efficiency (lower BSFC). As load increases and the engine becomes more susceptible to knock, by maintaining optimum spark timing over more of the operating range the higher-RON fuels enable efficient operation over a larger portion of the range. This improvement in thermal efficiency can be clearly seen by comparing the size of the central area of best efficiency shown on Figure 3 for each fuel grade. On viewing the upper right portion of each chart, it is apparent that RON plays a key role in improving efficiency at high engine speeds and loads, due to earlier ignition timing. While overfuelling is used in the engine to protect exhaust system components, advancing the ignition timing reduces the extent to which this option needs to be used.

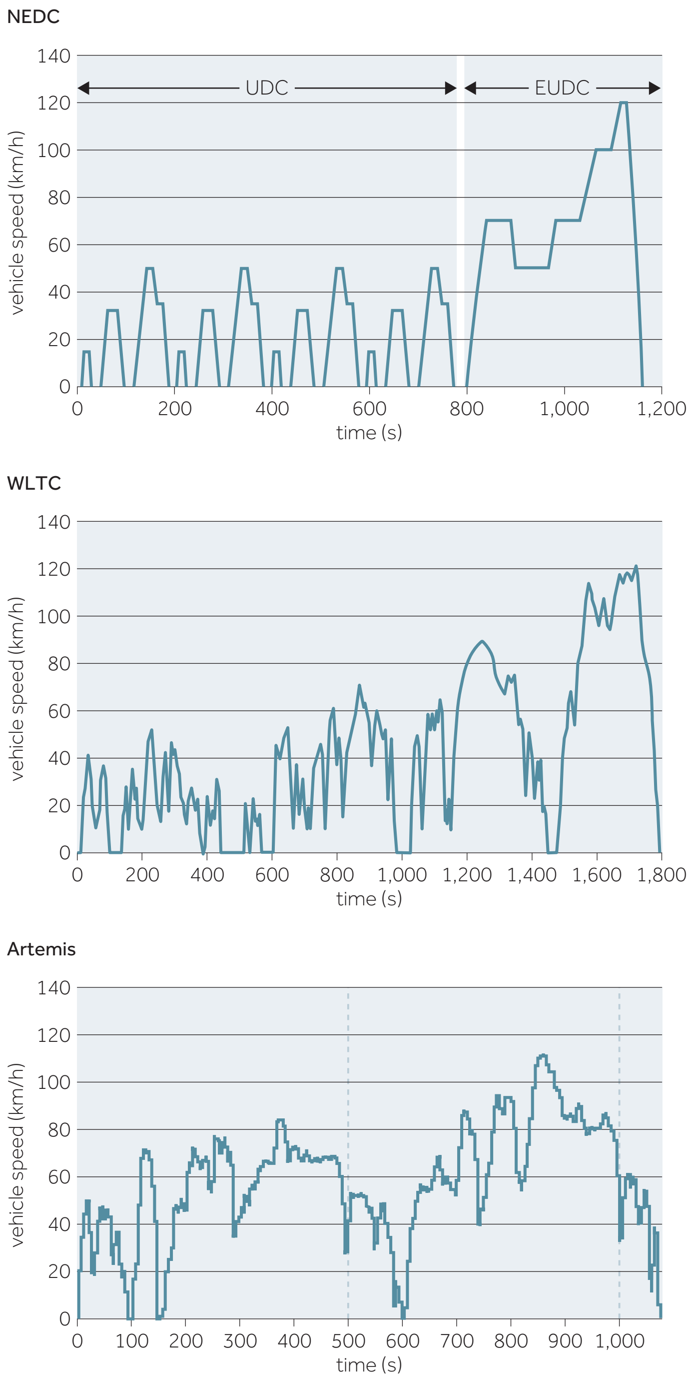
Figure 3: Contour plots of BSFC for different fuels



Drive cycles and modelling

Four test cycles were chosen for modelling. The NEDC (New European Drive Cycle) is the test cycle which, historically and until recently, was used for the homologation of vehicles. It consists of two parts—the urban drive cycle (UDC), and the extra-urban drive cycle (EUDC) which has higher speeds and less transience than the UDC. The Worldwide harmonized Light-duty Test Cycle (WLTC) contains a mix of far more realistic driving characteristics and range of speeds than the NEDC, and has been developed to replace the NEDC in vehicle homologation testing. In addition to these two test cycles, two higher-load test cycles were used: (i) the Real Driving Emissions (RDE) test cycle performed on a chassis dynamometer, which mimics a real route on roads around Northampton UK, the home of the MAHLE Powertrain headquarters; and (ii) the Artemis cycle, an older cycle that was also designed to mimic the more transient operation of on-road use. The NEDC, WLTC and Artemis cycles are shown in Figure 4 on page 8.

Figure 4: The NEDC, WLTC and Artemis chassis dynamometer test cycles

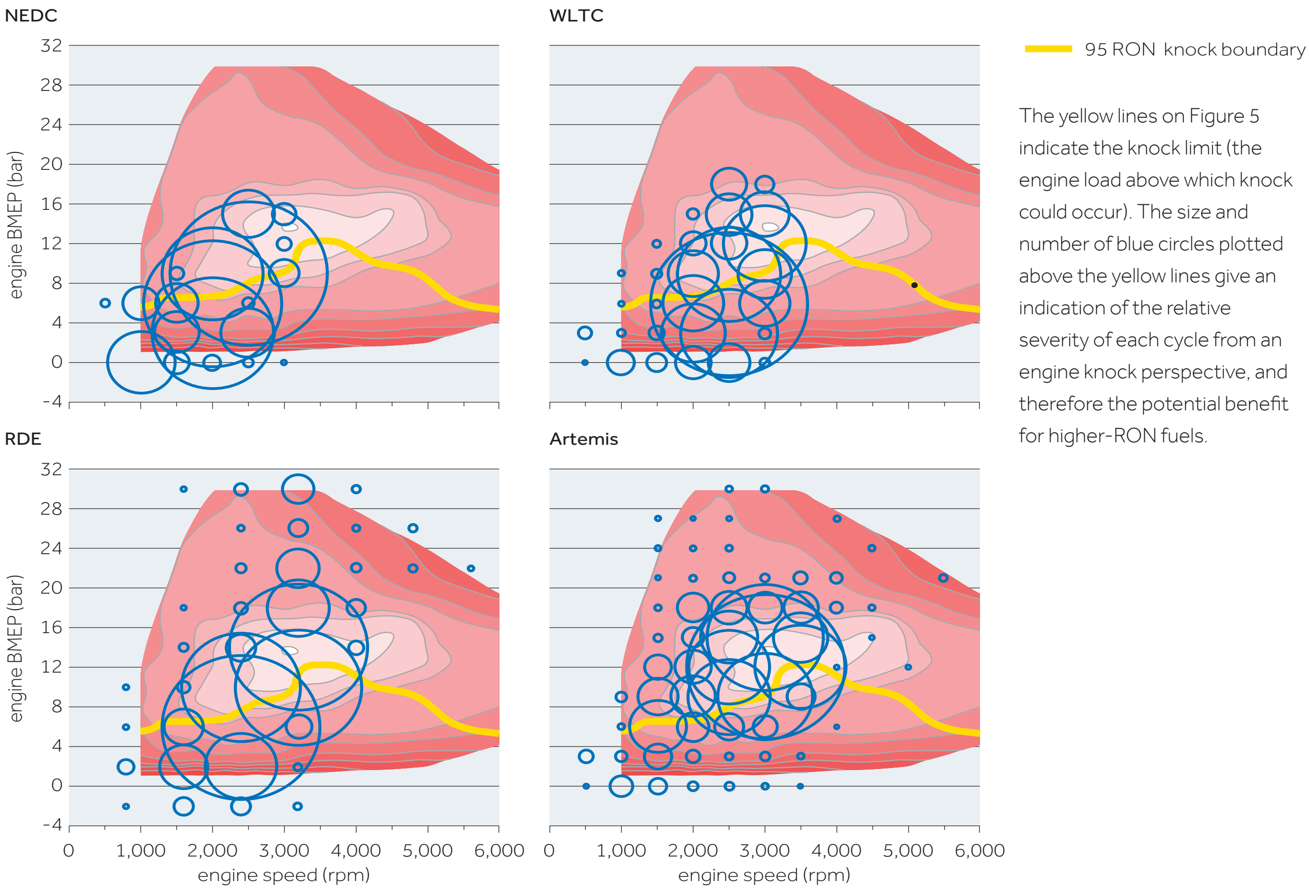


A vehicle simulation was performed using GT-Drive software, a dynamic model which was an updated version of the model used in a previous study.[4] The software enables virtual 'vehicles' to be built and tested over different drive cycles to evaluate fuel consumption and pollutant emissions. To produce a representation of the engine, the GT-Drive model uses the map of measured fuel flow rate against engine speed and load. This map is obtained from dynamometer measurements on the real engine taken during steady-state operation, under fully warm engine conditions, as described above. Full-load and friction curves are also measured and implemented as a function of accelerator position. A 'virtual driver' was constructed and used to generate the required system inputs such as throttle, brake, clutch and gear selection signals, to follow the time-speed profiles of the various drive cycles investigated. This 'virtual driver' looks one time-step ahead (around 0.25 seconds) and calculates the torque necessary to achieve the required vehicle acceleration in order to match the requested future vehicle speed. The calculated torque request is passed on to the engine or brake parts of the model. To account for changes in speed and cold-start fuelling characteristics of the real engine, a number of correction tables and equations are implemented into the model.

The inputs required for the creation of the model combine parameters related to vehicle specifications used for driving resistance and powertrain data for efficiency, torque and energy flow while delivering the power demanded. Vehicle specifications were either obtained via manufacturers' information or from direct measurements, and were finely adjusted so that road loads, such as aerodynamic drag and wheel rolling resistance, could be accurately represented. To capture the actual energy losses for the vehicle under evaluation, a vehicle coast-down test was performed, and the measured driving resistance employed in the correlated model for the technology and fuel assessment over the selected drive cycles.

The speed-load plots in Figure 5 demonstrate the benefits that can be achieved through the use of higher-octane fuels. The yellow lines indicate the knock limit (the engine load above which knock could occur with standard gasoline), and the position (speed-load coordinate of the operating point) and size (frequency of occurrence) of blue circles plotted above the line give an indication of the relative severity of each cycle from an engine knock perspective, and therefore the potential benefit for higher-RON fuels. These benefits translate to the drive-cycle fuel efficiency for each fuel and cycle combination presented in Table 2.

Figure 5: Speed-load plots for different test cycles



The yellow lines on Figure 5 indicate the knock limit (the engine load above which knock could occur). The size and number of blue circles plotted above the yellow lines give an indication of the relative severity of each cycle from an engine knock perspective, and therefore the potential benefit for higher-RON fuels.

Table 2: Simulated fuel consumption for each fuel and driving cycle

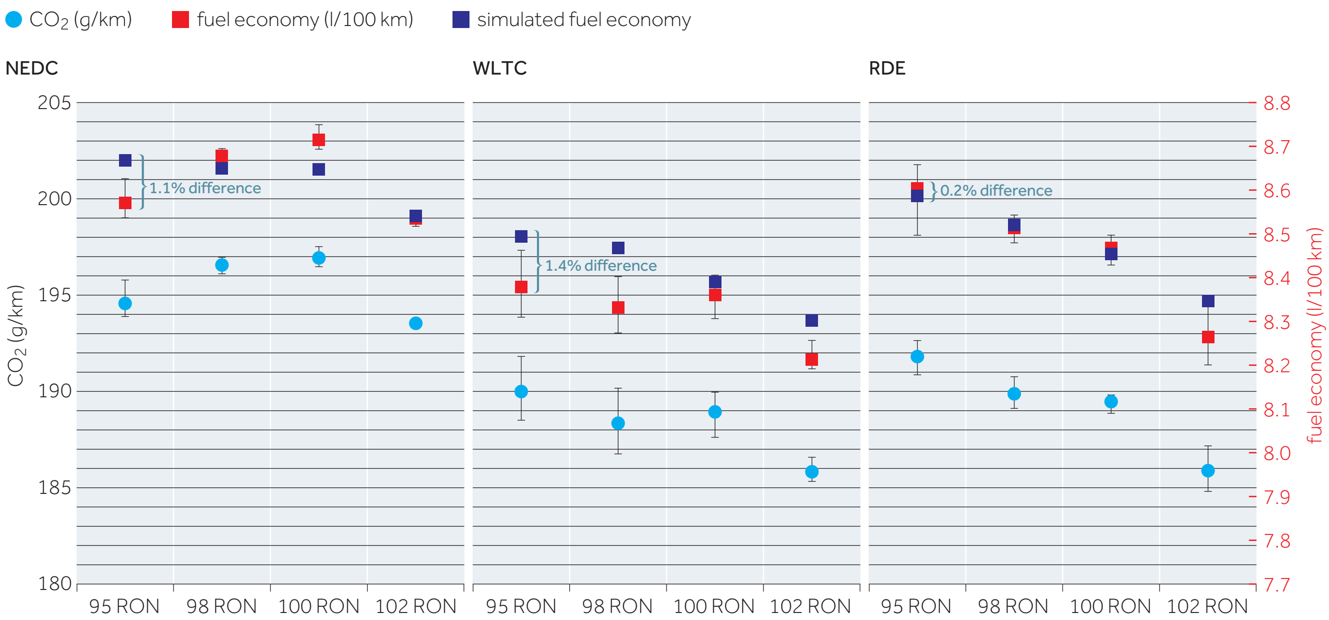
	95 RON	98 RON	100 RON	102 RON	95 RON	98 RON	100 RON	102 RON
Drive cycle	litres/100 km				% improvement vs 95 RON			
NEDC	7.078	7.062	7.019	6.954	-	0.22	0.83	1.75
WLTC	7.663	7.640	7.552	7.486	-	0.29	1.44	2.3
RDE	8.129	8.022	7.927	7.827	-	1.32	2.48	3.72
Artemis	8.34	8.245	8.168	8.075	-	1.14	2.06	3.17

Fuel economy benefits associated with an increase in RON from 95 to 102 of between 1.75% and 3.72% were simulated, with the lowest benefit being seen over the NEDC drive cycle, and the greatest over the chosen RDE cycle. For the NEDC cycle, the engine operates at BMEP levels below the knock limit threshold for most of the cycle, and therefore the effect of higher RON fuels is relatively small. The WLTC cycle is operated at slightly higher loads, although the greater part of the cycle is still below the 95 RON knock limit. In addition, both the RDE cycle and the Artemis cycle operate at significantly higher loads compared to the NEDC or the WLTC cycles and, therefore, showed fuel economy improvements when higher RON fuels were used due to less overfuelling needed than for lower RON fuels. These results are qualitatively and quantitatively consistent with those obtained in BP's work. They also demonstrate that the efficiency gain increases continuously with the RON increase, meaning that each step increase in RON between RON 95 and RON 102 is beneficial to fuel consumption for this high compression ratio engine. As far as the real driving conditions are concerned, a gain of 1.3% can be added due to the compression ratio increase from 10.2:1 to 12.2:1 as demonstrated in BP's work, leading to a ~5% fuel consumption benefit, which is again consistent with BP's results.

Vehicle testing

Following the completion of the engine test-bed testing and modelling phase, the engine was fitted within the chassis of a D/E segment car for chassis dynamometer testing. This vehicle was originally equipped with a 2.0 litre, turbocharged direct-injection engine of similar performance to the test engine. The vehicle was tested using three out of the four simulated test cycles—NEDC, WLTC and RDE—on the chassis dynamometer (rolling road). The RDE test cycle chosen was the same as that used for the modelling exercise for direct comparison, and was chosen as it represented an average cycle in terms of those available for all the fuels tested. Figure 6 shows the carbon dioxide (CO_2) and fuel economy results for the measured test cycles.

Figure 6: Measured CO_2 and fuel economy results versus simulated fuel economy results



In each case, the results shown are the average of each of three repeats, and the bars show the range of data round the average points. Both the WLTC and the RDE showed downward trends as RON increased, with no overlap between the results from the 102 RON fuel and the other fuels. The NEDC results were less clear, but were consistent with the modelling, and in line with the residency maps including the amount of time spent in low-load versus high-load conditions. The modelled fuel economy results are also superimposed on the charts, and it can be seen that the NEDC modelled result at 95 RON appears to follow the same trend as the others. In general the difference between the modelled and measured results was around 1.5% and below, which was considered to be very good, with the lowest difference in the RDE results and the biggest difference with the WLTC, which was more similar to the NEDC.

Conclusion

These results add to an increasing body of data which shows that when fuels and vehicles are optimised together to take advantage of higher-RON fuels, significant improvements in efficiency and CO_2 emissions can be demonstrated, particularly under high-load and real-driving conditions. They also add to our understanding of how vehicles and fuels together can play a role in meeting future CO_2 targets.

Acknowledgements

Concawe would like to thank MAHLE Powertrain Ltd for conducting the testing and modelling for the programme, and Coryton Advanced Fuels for fuel blending.

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Understanding the process of setting air quality limit values and the associated compliance challenge

A Concawe modelling study examines how annual average PM and NO_2 concentrations would vary under different emission reduction scenarios, and assesses the cost and practicability of achieving compliance with air quality limit values (AQLVs). The study highlights the importance of undertaking a risk management process when setting AQLVs, to ensure that any new limit value can be achieved in practice.

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Introduction

In 2018, the European Commission initiated a fitness check[1] of the two EU Ambient Air Quality (AAQ) Directives (Directives 2008/50/EC[2] and 2004/107/EC[3]). A fitness check evaluates the relevance, effectiveness, efficiency, coherence and added value to the EU of a Directive. The AAQ Directives set air quality standards and require Member States to monitor and/or assess air quality in their area in a harmonised and comparable way.

The results of the fitness check will be used to assess whether the AAQ Directives remain the appropriate legislative instruments for protecting the environment and the European population from adverse impacts on human health associated with air pollutants.

In addition, as it has been stated by the European Commission in its Clean Air Programme for Europe, the long-term objective for air quality in the EU is to achieve no exceedances of the World Health Organization (WHO) guideline levels for human health.[4,5] These guideline concentration values are lower than the limit values set in the AAQ Directives for some pollutants.

Many Member States have difficulty in complying with the current conditions of the Directives and specifically meeting air quality limit values (AQLVs) that came into force as long ago as January 2010. The fitness check process therefore has a difficult task ahead. A recommendation in line with EU policy objectives to revise the AAQ Directives to include more stringent AQLVs will be difficult to achieve, considering efforts made by Member States to comply with present values.

The WHO guidelines[4] state that:

> *'... it should be emphasized, however, that the guidelines are health-based or based on environmental effects, and are not standards per se. In setting legally binding standards, considerations such as prevailing exposure levels, technical feasibility, source control measures, abatement strategies, and social, economic and cultural conditions should be taken into account.'*

Consequently, the fitness check and the Directive revision process that ensues should follow a two-step process of firstly assessing the environmental and human health risks presented by concentrations of air pollutants (risk assessment step), and secondly assessing how these risks may be managed (risk management step).

A consequence of underestimating the importance of the risk management step would be to incur potentially excessive costs without being effective, as illustrated by the case of nitrogen dioxide (NO_2). Risk management is the process of assessing how emissions of pollutants can be controlled and at what cost, and how successful the control measures are in reducing pollutant concentrations in the air. The WHO air quality guideline value for the annual mean concentration of 40 µg/m^3 was adopted as an AQLV for NO_2 in Europe. This has since proven to be extremely difficult to achieve, and many areas of Europe are non-compliant despite significant emission reduction efforts. In the US, the ambient air quality standard for NO_2 was set at 100 µg/m^3, which is more than twice the WHO guideline value.[6] If an AQLV higher than the WHO guideline of 40 µg/m^3 had been adopted in Europe, progress to reduce concentrations of NO_2 towards the WHO guideline value could have been made in a more measured way, and without the 'pressures' that non-compliance brings (e.g. the strict time frame for the adoption of emission control measures).

A more measured approach has been adopted for particulate matter ($PM_{2.5}$). The annual mean EU AQLV for $PM_{2.5}$ was set at 25 µg/m^3 compared to the WHO air quality guideline value of 10 µg/m^3. Since then, emission measures have led to a steady reduction in $PM_{2.5}$ concentrations. The revision of the AAQ Directives will certainly examine the level at which a new limit value might be set, but the risk management process must be robust enough to ensure that any new value can be achieved.

The risk management process has to consider how emission reductions affect the level of pollutant concentrations in the air. There are many emission sources, and each source reduction has an associated investment cost. These costs can vary widely. As the target value for the concentration of a pollutant in the air is reduced, finding the balance of mitigation measures that have the least overall cost gets more difficult, and the cost itself increases dramatically. Solving the problem is made more difficult by the formation of secondary pollutants in the atmosphere; these make the relationship between emission and concentration dependent on geography, climatic conditions and transboundary effects.

To assess the cost and the practicability of achieving compliance with lower ambient AQLVs, Concawe commissioned Aeris Europe to carry out a study that examines how annual average air concentrations of PM and NO_2 would vary under some potential emission reduction scenarios. The results were evaluated at each of the approximately 3,000 European air quality monitoring stations currently in place and are expressed in terms of compliance, i.e. whether or not the annual average concentration at the station would be less than a limit value. For brevity, this article examines compliance in two countries, Poland and France, which have been chosen as representative examples to demonstrate the results of the study.

Modelling approach

The concentrations of NO_2 and PM at the monitoring stations are predicted, for each of the emissions scenarios examined, using the AQUIReS+ model.[7] The model uses a gridded emission inventory and source-receptor relationships[8] that relate a change in emission to a change in concentration. These derive from regional chemical transport models (EMEP[9], CHIMERE[10]) used in air policy studies. The model takes into account the local environment, traffic and topographical characteristics of each station. Model predictions are compared with data from the EEA Air Quality e-Reporting dataset[11] to ensure that the model performs sufficiently well to reproduce concentrations of pollutants over historic years. The cost of certain emission reduction scenarios is calculated using Concawe's in-house Integrated Assessment Model (IAM) SMARTER, which takes its values from the IIASA GAINS model[12] used to develop European environmental policy.

Emissions scenarios

Current legislation baseline

The starting point of the study is the Current Legislation (CLE) scenario—the official EU projection of how emissions (based on multiple sector contributions) will evolve in time. The CLE scenario takes account of economic growth and evaluates the impact of European legislation currently in force. Projections are made in five-year steps. The geographic distribution of emissions is accounted for at a fine scale, and national emissions for the EU 28 Member States are calculated by spatial aggregation.

The CLE scenario is described in the Thematic Strategy on Air Pollution (TSAP) Report #16, published by IIASA.[13,14,15] The focus of that report is on $PM_{2.5}$, NO_x, SO_2, NH_3 and NMVOCs. For simplicity the many source emissions are aggregated into 10 different sectors according to the SNAP (Selected Nomenclature for sources of Air Pollution) method.

Figure 1 shows the CLE emissions projections of $PM_{2.5}$ for France and Poland, broken down by SNAP sector. $PM_{2.5}$ emissions are seen to decrease from 2015 onwards in both countries, falling by 30% in France and 20% in Poland by 2030. In both countries the largest contributor to $PM_{2.5}$ is residential combustion. In France, this accounts for more than 40% of total $PM_{2.5}$ emissions up to 2020, dropping to 35% of $PM_{2.5}$ emissions in 2030 (Figure 1a). In Poland, where coal and firewood are still widely used as domestic fuels, the contribution of residential combustion exceeds 70% of total $PM_{2.5}$ emissions in all years (Figure 1b).

Figure 1: Sectoral $PM_{2.5}$ emissions for France and Poland under the CLE scenario

(Source: IIASA GAINS TSAP report #16).

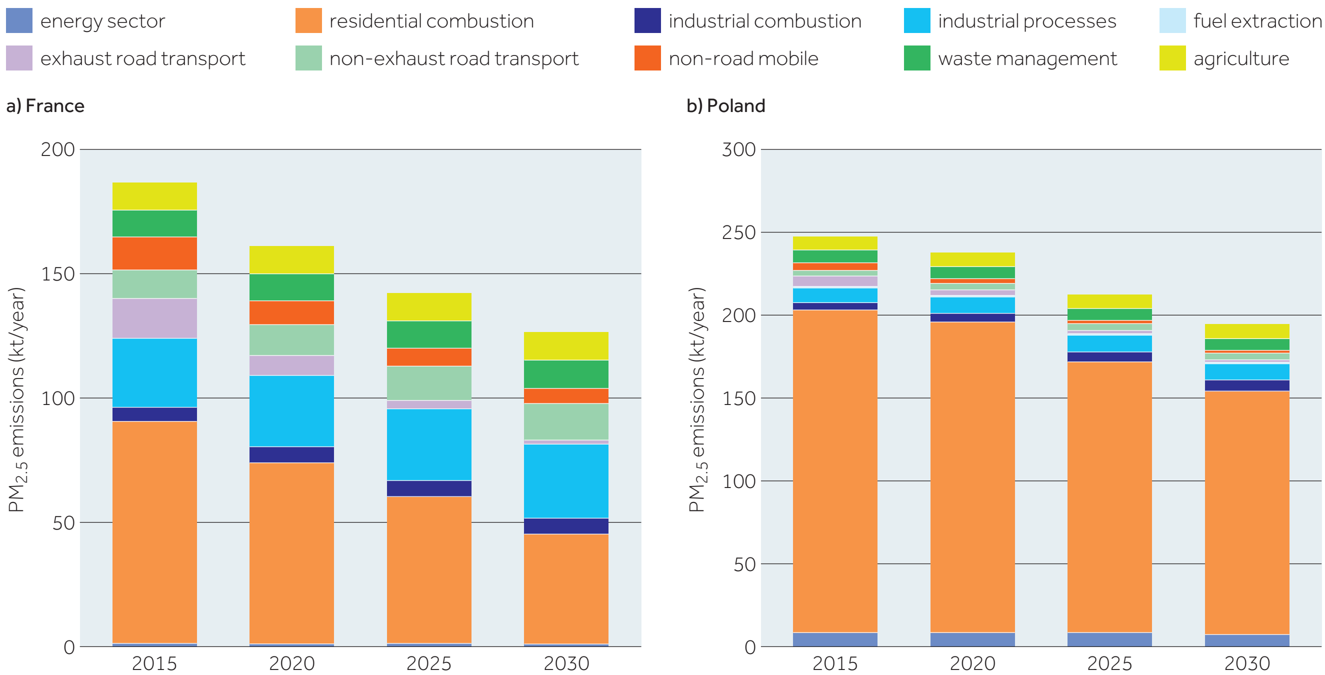
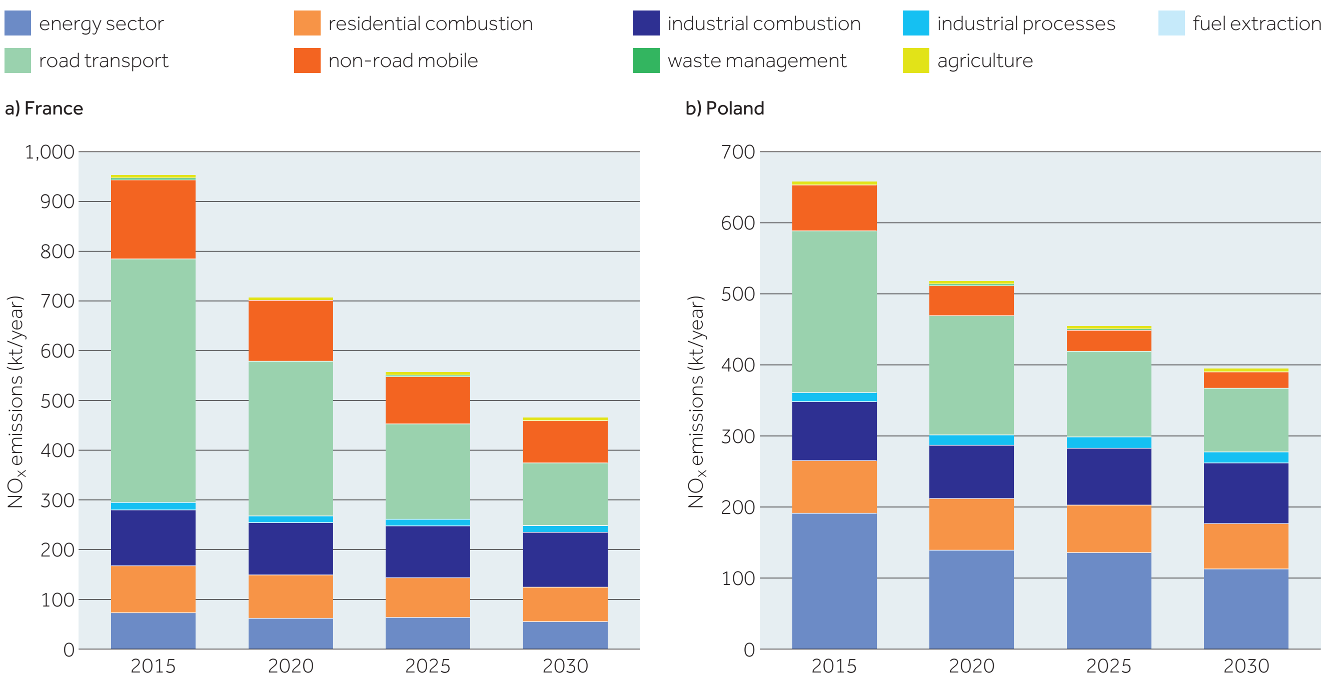


Figure 2 shows the CLE emissions projections of NO_x for France and Poland broken down by SNAP sector. Emissions show a clear downward trend in both countries. In 2030, NO_x emissions in France are expected to be 50% lower than in 2015 (Figure 2a), while in Poland the reduction is approximately 40% (Figure 2b).

In both countries, emissions of NO_x from transport are a significant but decreasing component of NO_x emissions. The reduction is due to the implementation of the Euro VI (for heavy-duty) and Euro 6 (for passenger) vehicle regulations and the progressive retirement of older vehicles from the fleet. The energy sector and industry are also significant contributors to total NO_x emissions. In Poland, the energy sector is expected to be the largest source of NO_x emissions after 2025.

Figure 2: Sectoral NO_x emissions for France and Poland under the CLE scenario

(Source: IIASA GAINS TSAP report #16).



Maximum Technically Feasible Reductions (MTFR) scenario

A second scenario used in policy planning is the Maximum Technically Feasible Reductions (MTFR) scenario. This is historically named and refers to the case where emissions from stationary sources are reduced by using all available technical measures. It gives a reference point for both 'minimum emissions' and 'maximum costs' for these sources. It is important to note that not all sources are included, and non-technical measures can also be used to reduce emissions. The implementation of non-technical measures would require specific political will, and their feasibility is not considered. Foreseen plant closures, such as the phasing out of some older fossil-fuelled power stations, are accounted for in the CLE scenario.

Optimised emissions scenarios

To estimate the cost contribution from traditional abatement measures used to reduce emissions from stationary sources, a number of optimised scenarios were generated over the range between the CLE and MTFR cases. The optimisation used aims to find the most cost-effective way to achieve a target. In these calculations the target is the EU-wide human health benefit associated with reducing concentrations of pollutants in the air. The results from the optimised scenarios are shown in the section on *Estimated costs of reducing the AQLV for $PM_{2.5}$ and NO_2* on pages 22–25.

Emissions scenarios evaluated

In addition to the CLE and MTFR scenarios described above, additional emissions scenarios are examined by Concawe. These scenarios involve measures that are not included as technical measures in the GAINS model and therefore have no attributed costs. They are non-technical measures, the implementation of which would require specific political will, and their feasibility is not considered. Table 1 provides a list of the additional scenarios examined in this study, and a brief description of each follows below.

Table 1: Scenarios examined in this study and the corresponding year(s).

SCENARIO	DESCRIPTION	INTRODUCTORY YEARS
1	Electrification of Passenger Car Diesel (PCD)	2025, 2030
2	Electrification of Passenger Car Gasoline (PCG)	2025, 2030
3	Electrification of Light-Duty Vehicles (LDV)	2025, 2030
4	Electrification of all Road Transport	2025, 2030
5	Early introduction of hypothetical EURO 7 PCD	2025, 2030
6	Substitution of Domestic Solid Fuels with Heating Oil	2025, 2030
7	Removal of Agricultural Ammonia (NH_3) Emissions (SNAP 10)	2030

Scenarios 1–4: Electrification of the vehicle fleet

Specific vehicle categories are assumed to be replaced by electric vehicles with zero tailpipe emissions of NO_x, PM ($PM_{2.5}$ and PM_{10}) and SO_2. Each substitution scenario is assumed to have an immediate effect on the vehicle category emissions from the year of introduction onwards.

The following substitutions with electric vehicles are explored individually:

- Scenario 1: Diesel passenger cars
- Scenario 2: Gasoline passenger cars
- Scenario 3: Light-duty vehicles
- Scenario 4: All vehicles (including heavy duty vehicles, buses/coaches and motorcycles/mopeds).

Non-exhaust emissions of $PM_{2.5}$ remain unmodified in these scenarios because there is no certainty as to how regenerative braking, heavier vehicles, changes in driving habits, etc. will affect total fleet tyre and brake wear.

Scenario 5: Introduction of a hypothetical Euro 7 emissions standard

In this scenario, all Euro 6 or earlier Euro standard (i.e. Euro 4, Euro 5, etc.) diesel passenger cars are assumed to be taken off the road and replaced with diesel passenger cars meeting a hypothetical Euro 7 standard. This hypothetical Euro 7 standard is derived from the GAINS database and varies by country. However, across Europe, this scenario results in an approximate 80% reduction in NO_x emissions for the PCD element of the fleet.

Scenario 6: Domestic solid fuel substitution

All solid fuel (coal, wood, other biomass) used in the domestic sector is substituted by either gas or heating oil. Emissions of $PM_{2.5}$, SO_2 and NO_x are considered. For $PM_{2.5}$, emission factors for heating oil have been used for the substitution to give a conservative estimate of the emissions reduction (97.5% reduction for oil compared with 99% for gas, on an energy released basis).

Scenario 7: Removal of NH_3 emissions

Scenario 7 assumes the removal of all ammonia (NH_3) emissions from the agricultural sector. It should be noted that Scenario 7 does not affect the emissions of primary PM and NO_x. However, NH_3 plays an important role in the formation of secondary PM, and therefore it can be an important contributor to total $PM_{2.5}$ concentrations. The impacts on PM concentrations are examined under this scenario.

Results

Projected emissions of primary $PM_{2.5}$ in 2030 are shown in Figure 3 for France and Poland. The 2030 emissions of NO_x are shown in Figure 4.

Figure 3: Projected $PM_{2.5}$ emissions for France and Poland in 2030 under the different scenarios examined

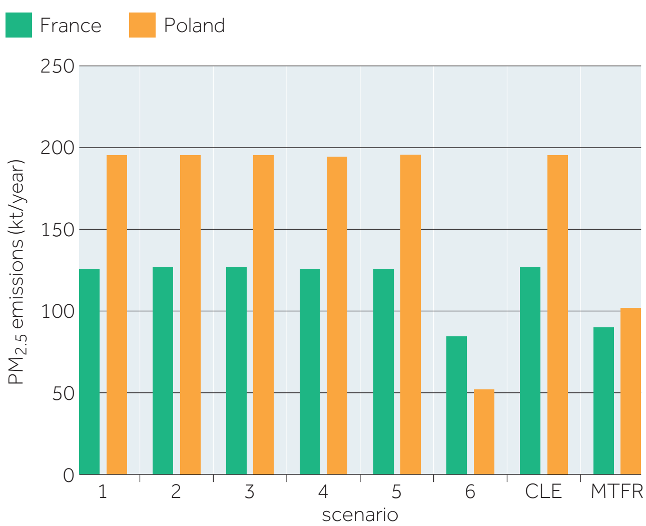
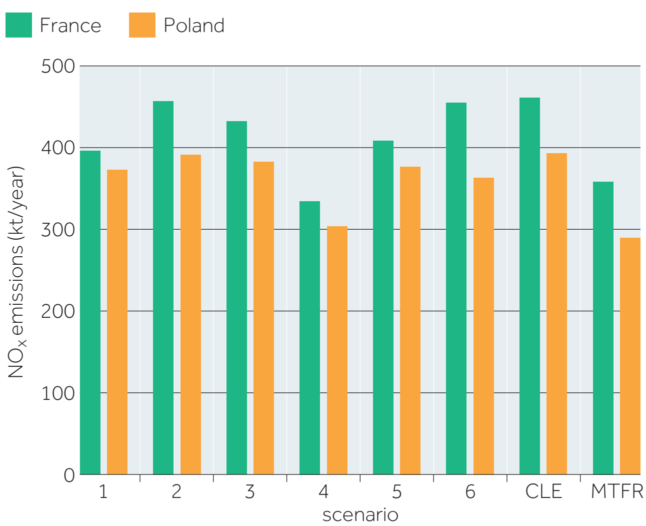


Figure 4: Projected NO_x emissions for France and Poland in 2030 under the different scenarios examined



Figures 5 and 6 on pages 19 and 21 show the predicted percentage of non-compliant monitoring stations for $PM_{2.5}$ and NO_2, respectively, in France and Poland, under the different scenarios examined. It is helpful to note the following with regard to these two figures:

- The left hand vertical axis represents the percentage of monitoring stations in the country where pollutant concentrations in the air do not meet the current AQLV for that pollutant ($PM_{2.5}$ on Figure 5; NO_2 on Figure 6). The percentage of monitoring stations for each scenario is shown by the blue bars. If there is no blue bar, all stations comply with the current AQLV for that pollutant.
- The right hand vertical axis represents the annual average concentration in the air of either $PM_{2.5}$ or NO_2, depending on the figure. The horizontal red line shows the current EU AQLV. The horizontal green line shows the current WHO guideline value for $PM_{2.5}$. For NO_2 the WHO guideline value and the EU AQLV are the same, and a red line is therefore used for both.
- The orange dashes for each scenario on the figures relate to the right-hand axis (pollutant concentration) and represent the highest concentration occurring at any monitoring station. The highest concentration may occur at different monitoring stations according to the scenario tested. If the orange dash lies above the EU AQLV (red line) the station is non-compliant and the distance above the line indicates by how much. If the orange dash lies above the green line ($PM_{2.5}$) this indicates the gap between the highest concentration and the WHO guideline value.
- The horizontal axis combines time and the scenarios listed above, and shows the CLE results for 2015, 2020, 2025 and 2030, and the MTFR results for 2030. The results of the individual scenarios are also shown for 2025 and 2030.

Particulate matter ($PM_{2.5}$)

(a) France

Figure 5a shows the results for $PM_{2.5}$ in France. The EU AQLV for the annual average $PM_{2.5}$ concentration is 25 µg/m^3 and the WHO air quality guideline value for $PM_{2.5}$ is 10 µg/m^3.

In 2015, only a small number of stations are non-compliant with the EU AQLV, while from 2020 onwards, $PM_{2.5}$ compliance is achieved at all stations in France.

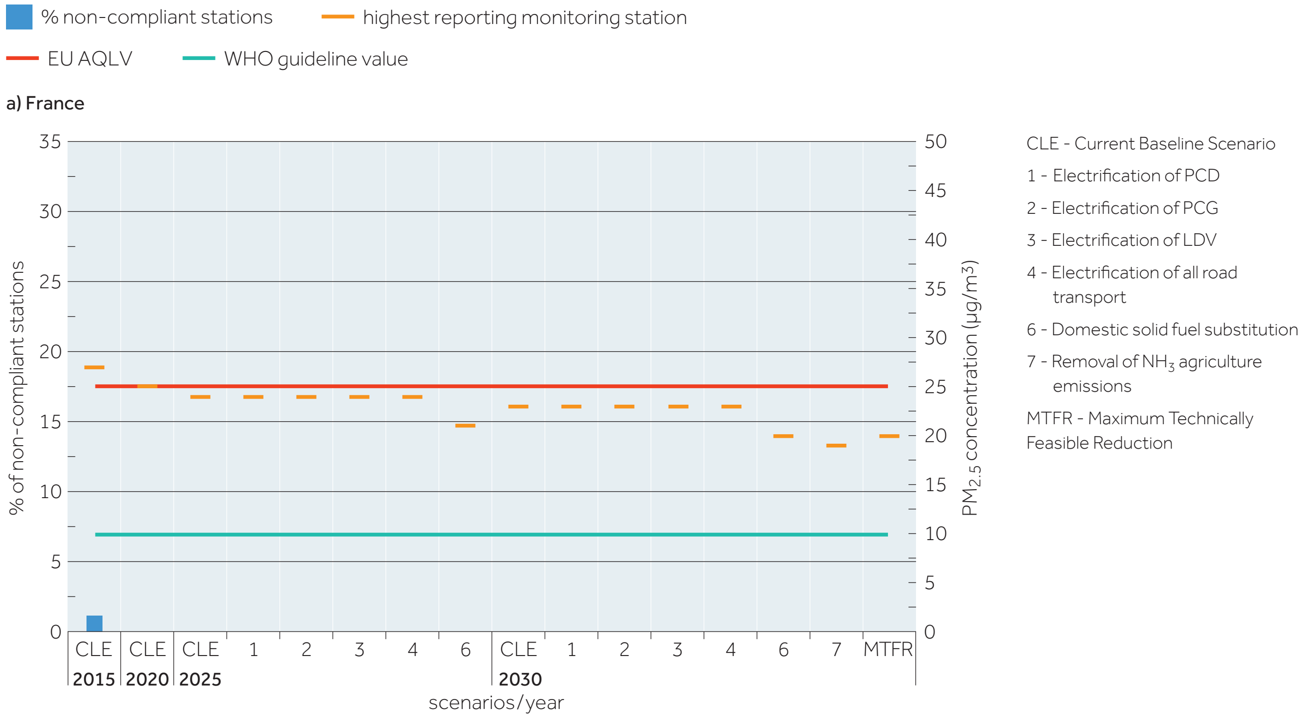
In 2025, scenarios 1, 2, 3 and 4 have little impact on the highest $PM_{2.5}$ concentration which is similar to that expected under the CLE scenario. A reduction in the EU AQLV of more than 1 µg/m^3 would result in at least one monitoring station reporting an exceedance (non-compliance). The substitution of domestic solid fuel (scenario 6) gives the largest reduction in $PM_{2.5}$. However, note that the distance to the WHO guideline value of 10 µg/m^3 is still large in this scenario (>11 µg/m^3 in 2025).

In 2030, all maximum concentrations are reduced, though not by much. Scenario 6 (domestic fuel substitution) is as effective as the MFTR scenario in this compliance test. The sensitivity scenario of eliminating NH_3 emissions from the agricultural sector (Scenario 7) gives only a small further reduction in $PM_{2.5}$ concentration.

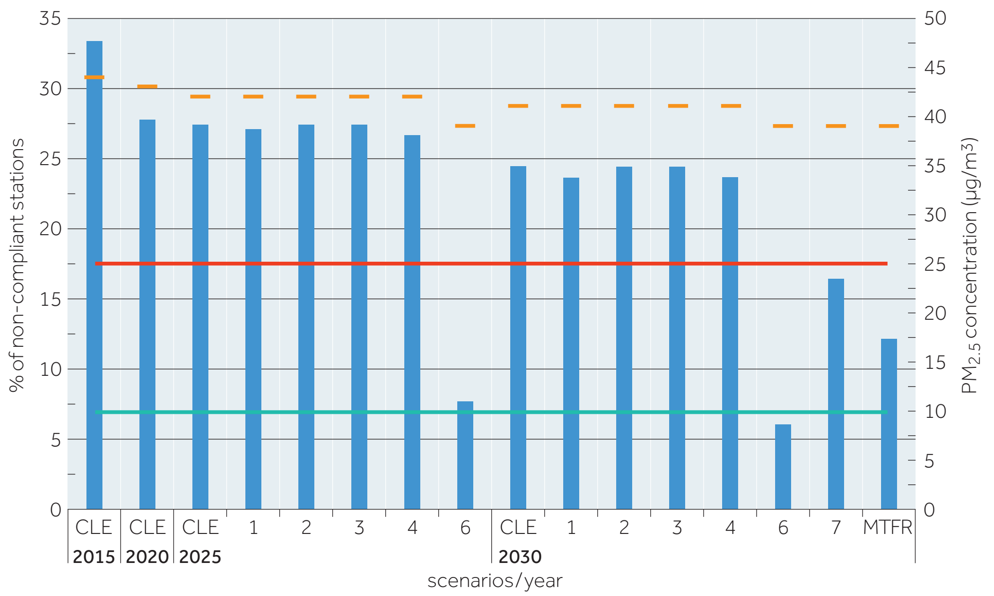
Figure 5: Predicted percentage of $PM_{2.5}$ non-compliant stations in France and Poland over the years and under the different scenarios examined

The blue bars on the figures below relate to the left axis. The orange dashes indicate the predicted changes in $PM_{2.5}$ concentration (µg/m^3) at the highest-recording monitoring station in each country, and these relate to the right axis.

a) France



b) Poland



None of the scenarios examined here is able to reduce the concentration of $PM_{2.5}$ at the highest-recording monitoring station in France to the WHO guideline value of 10 μg/m^3. A significant downward change in the EU AQLV is likely to present compliance problems.

(b) Poland

Figure 5b shows results for $PM_{2.5}$ in Poland. Under current legislation, Poland is predicted to have significant compliance problems with $PM_{2.5}$ across about a quarter of the monitoring network through to 2030.

Of the scenarios considered, only Scenario 6 (the substitution of domestic solid fuels with heating oil) has a large effect on reducing the number of non-compliant monitoring stations. Maximum concentrations remain significantly higher than the EU AQLV even in 2030, and full compliance is not predicted to be achieved.

Nitrogen dioxide (NO_2)

(a) France

Figure 6a shows the results for NO_2 in France. The current EU AQLV is 40 μg/m^3 and equal to the WHO air quality guideline value for NO_2.

The results show that, despite a steady reduction in NO_x emissions with time, compliance with the EU AQLV still remains an issue, both under the CLE scenario and the more ambitious scenarios considered.

In 2025, scenarios 1, 3, 4 and 5 all reduce the highest NO_2 concentration and the number of non-compliant stations compared to the CLE scenario. Scenarios 2 and 6 have no substantial effect.

In 2030, the pattern is the same and, although concentrations are lower, there are still exceedances at several monitoring stations. Even if the extreme measure of electrification for the entire vehicle fleet was implemented (Scenario 4), non-compliance is indicated at one site. This is an important finding as it relates to the inclusion of a risk management process in setting AQLVs, as the application of technical measures may not be sufficient to enable France to meet the current EU AQLV, even if cost and social considerations are not barriers.

Reducing the EU AQLV clearly has important implications for making compliance more challenging in France even in 2030 and with maximum abatement measures in place.

(b) Poland

Figure 6b shows results for NO_2 in Poland. By 2025 all stations should be compliant with the current EU AQLV under the CLE scenario, and also under the other emission reduction scenarios considered. As in France, scenarios 1, 3, 4 and 5 are predicted to reduce the highest NO_2 concentrations. Measures on transport have a larger effect than maximum reductions on stationary sources. Under the ambitious Scenario 4 (complete electrification of road transport), the maximum indicated NO_2 concentration is 25 μg/m^3 but, realistically, concentrations are likely to remain above those indicated by the MTFR scenario (34 μg/m^3).

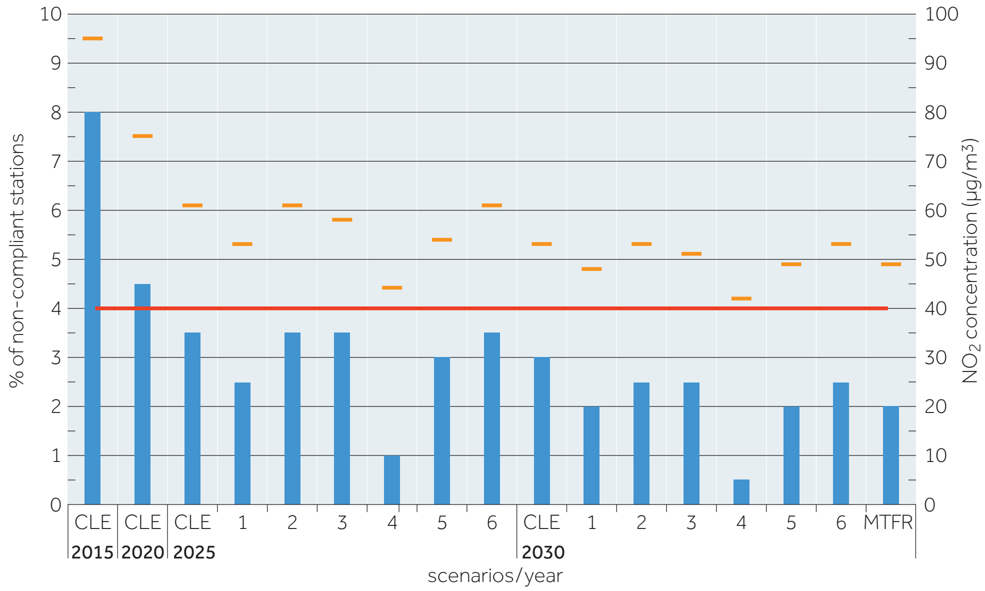
Figure 6: Predicted percentage of NO_2 non-compliant stations in France and Poland over the years and under the different scenarios examined

The blue bars on the figures below relate to the left axis. The orange dashes indicate the predicted changes in NO_2 concentration (µg/m³) at the highest-recording monitoring station in each country, and these relate to the right axis.

% non-compliant stations — highest reporting monitoring station

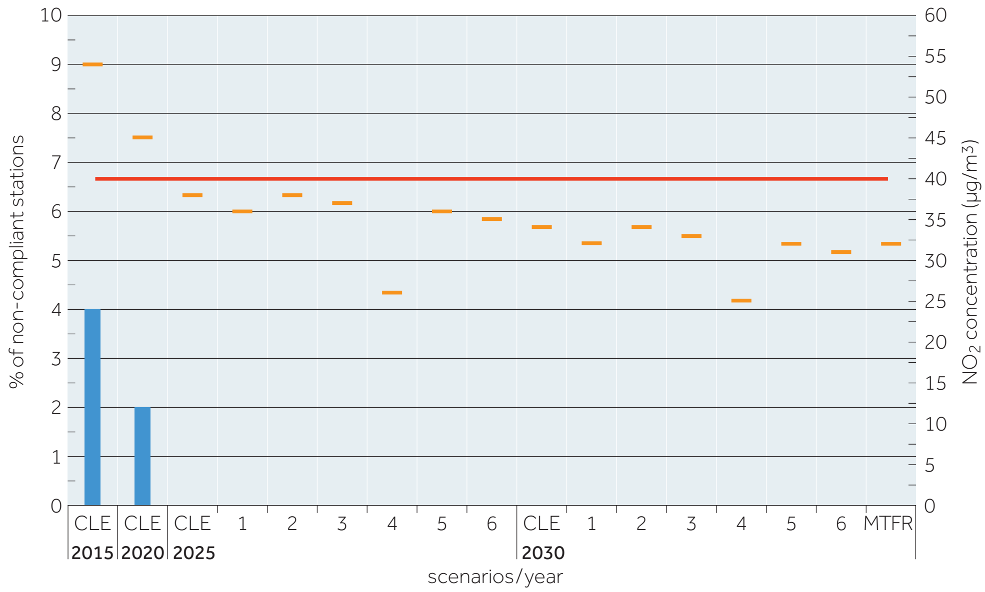
EU AQLV / WHO guideline value

a) France



CLE - Current Baseline Scenario
1 - Electrification of PCD
2 - Electrification of PCG
3 - Electrification of LDV
4 - Electrification of all road transport
5 - Introduction of Euro 7 PCD
6 - Domestic solid fuel substitution
MTFR - Maximum Technically Feasible Reduction

b) Poland



Estimated costs of reducing the AQLV for $PM_{2.5}$ and NO_2

A number of optimised scenarios were generated, over the range between the CLE and MTFR cases, to estimate how costs would increase, if traditional abatement measures on stationary sources were implemented to reduce concentrations in the most economic way. These are estimated incremental costs beyond the associated cost of implementing the measures described under the CLE scenario, which is already significantly high. The costs were calculated using Concawe's in-house Integrated Assessment Modelling (IAM) tool, SMARTER, which takes its values from the IIASA GAINS model[12] used to develop European environmental policy.

The optimised scenarios follow the 'gap closure' concept adopted during the Clean Air for Europe Programme[5] as an indicator of policy ambition level. The gap closure can be considered as the expected further reduction of health-related impacts (i.e. improvements in life expectancy) that can be achieved in moving from the CLE scenario to the MTFR scenario. For example, a '70% gap closure' indicates an optimised emission scenario where additional measures beyond the CLE scenario have been implemented in the most cost-effective way, and result in an additional 70% reduction in health-related impacts (beyond the CLE scenario). Respectively, the '0% gap closure' is equivalent to the health-related impacts reductions achieved under the CLE scenario, and a '100% gap closure' is the maximum further reduction of health-related impacts that can be achieved beyond the CLE scenario and which is equivalent to the MTFR scenario.

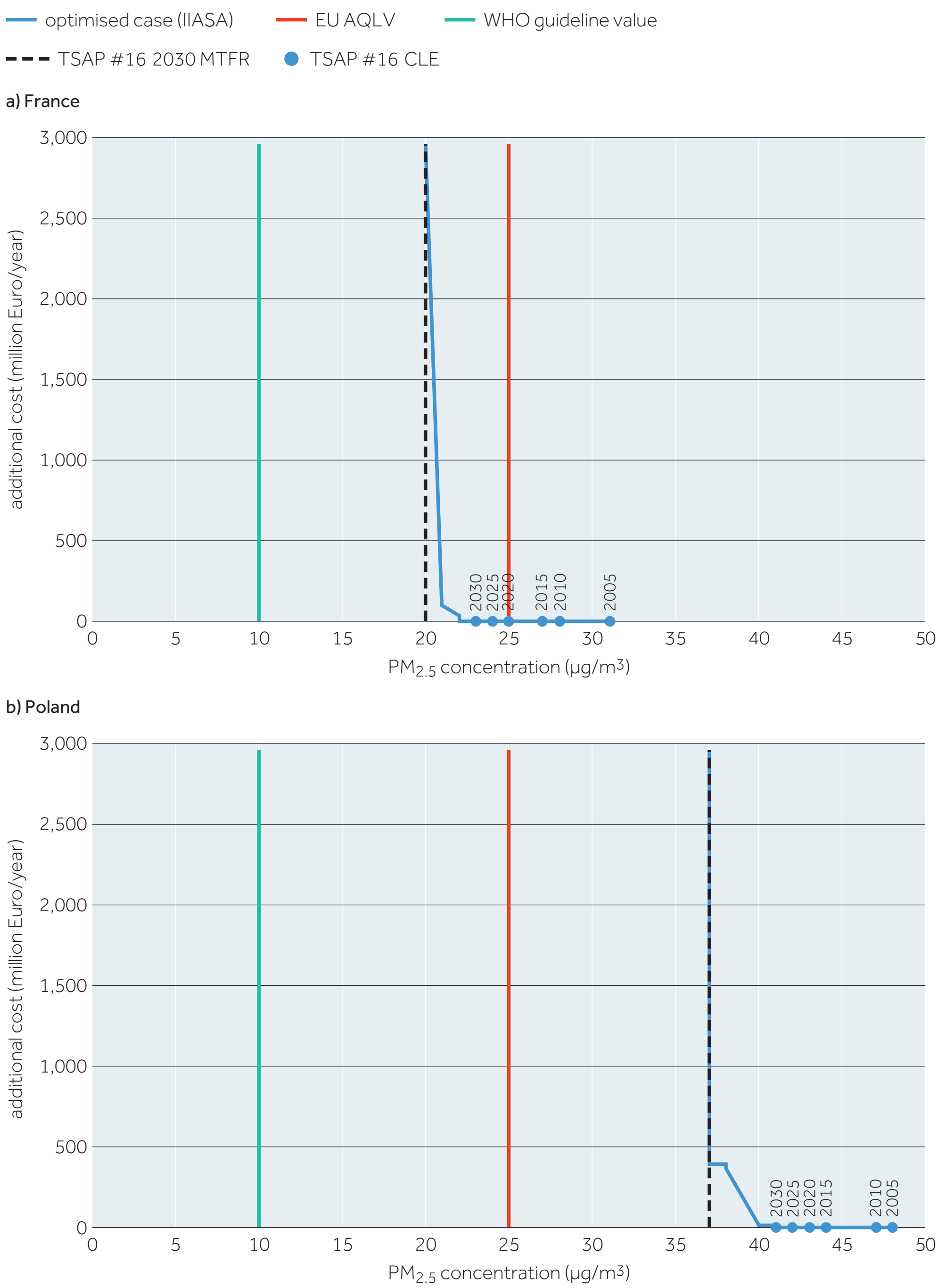
It should be noted that the additional emissions scenarios described under *Emissions scenarios evaluated* on pages 16–17 are not considered here, since they involve measures that are not included as technical measures in the GAINS model and therefore the associated cost is not known.

Figures 7 and 8 on pages 23 and 25 show the predicted reductions in $PM_{2.5}$ and NO_2 concentrations, respectively, for the highest-recording monitoring station in France and in Poland, compared to the associated cost, under different optimised scenarios; these scenarios assume the adoption of additional measures beyond the CLE scenario (2005–2030) and towards the MTFR scenario, following the 'gap closure' concept. It is helpful to note the following with regard to these two figures:

- The left hand vertical axis represents the annualised costs of meeting the target value considered in the optimisation procedure (i.e. the EU-wide human health benefit associated with reducing air concentrations). These incorporate the discounted capital and operating cost of introducing new measures using the GAINS methodology. Costs are additional to those already agreed in reducing emissions according to the CLE scenario.
- The horizontal axis represents a range of concentrations of $PM_{2.5}$ (Figure 7) and NO_2 (Figure 8). The vertical red line shows the current EU AQLV. The vertical green line shows the current WHO guideline value for $PM_{2.5}$.
- On each graph, a blue line is constructed using the optimisation procedure to determine how costs would increase if emission reductions beyond the CLE scenario were pursued in the most economic manner. The highest concentration over all monitoring stations in the country that is associated with these measures is used on the horizontal axis to plot this line.

Figure 7: Predicted reduction in $PM_{2.5}$ concentration for the highest-recording monitoring station in France and Poland

Predicted concentrations are compared to the associated cost, under different optimised scenarios that assume the adoption of additional measures beyond the CLE scenario (2005–2030) and towards the MTFR scenario, following a 'gap closure' concept.



Particulate matter ($PM_{2.5}$)

(a) France

Figure 7a shows the results for $PM_{2.5}$ in France. There are zero extra costs for each of the CLE scenarios from 2005–2030 (blue dots on the Figures) as the cost of achieving these reductions is already accepted.

$PM_{2.5}$ is significantly reduced as a result of the agreed measures under CLE. The current EU AQLV is met in 2020. For additional $PM_{2.5}$ reduction measures beyond CLE, there is an associated cost which rapidly increases when moving towards the MTFR scenario. In the MTFR scenario, a $PM_{2.5}$ concentration of 20 µg/m^3 is achieved, still significantly above the WHO guideline, but at a very high additional cost of some 3,000 million €/year.

(b) Poland

Figure 7b shows the results for $PM_{2.5}$ in Poland. As seen previously, $PM_{2.5}$ concentrations at the monitoring stations exceed the EU AQLV, and the application of technical measures will not result in the current EU AQLV being met despite the additional cost of some 3,000 million €/year. Interventions, such as those explored in the non-technical measures referred to in the section on *Emissions scenarios* (pages 14–17) would be required. For Poland, the largest reduction seen in the scenarios evaluated is associated with the substitution of domestic solid fuels by a lower-emission alternative. The cost of this substitution, however, has not been considered in the IIASA GAINS model.

Nitrogen dioxide (NO_2)

(a) France

Figure 8a (page 25) shows the results for NO_2 in France. As seen previously, the application of MTFR measures does not lead to full compliance with the existing EU AQLV, and the gap at the highest-recording monitoring station is significant, at 10 µg/m^3. The additional costs involved rise to beyond 600 million €/year under the MTFR scenario.

(b) Poland

Figure 8b (page 25) shows the results for NO_2 in Poland. There are no compliance issues under the CLE scenario. Current legislation reduces the NO_2 concentration at the highest-recording monitoring station to just over 30 µg/m^3. The application of MTFR could reduce this to about 26 µg/m^3 at an additional cost of ~350 million €/year.

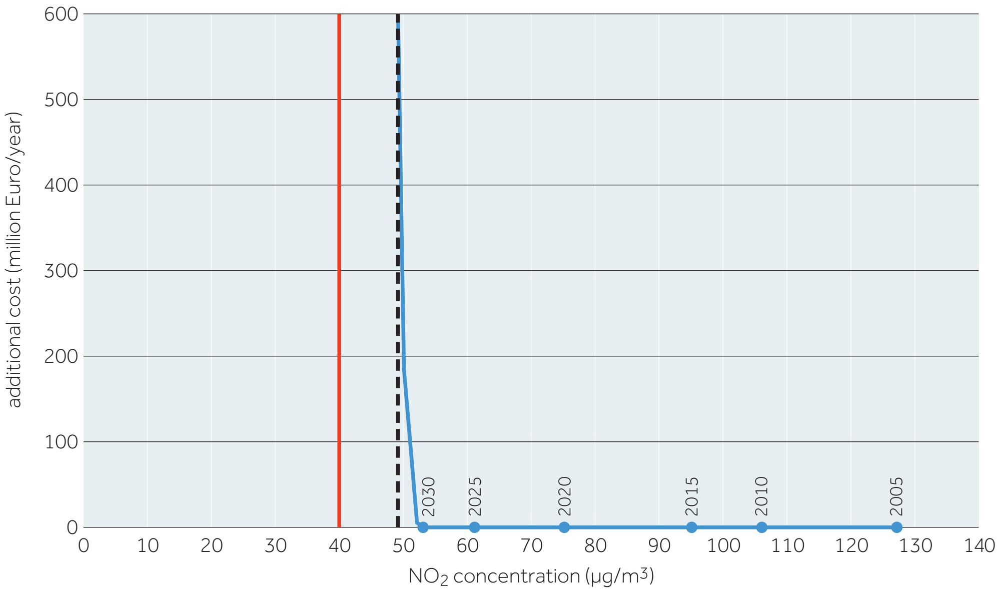
This demonstrates that the situation in each Member State is unique, and that the country variation should be considered when setting binding limit values by the inclusion of a risk management step.

Figure 8: Predicted reduction in NO_2 concentration for the highest-recording monitoring station in France and Poland

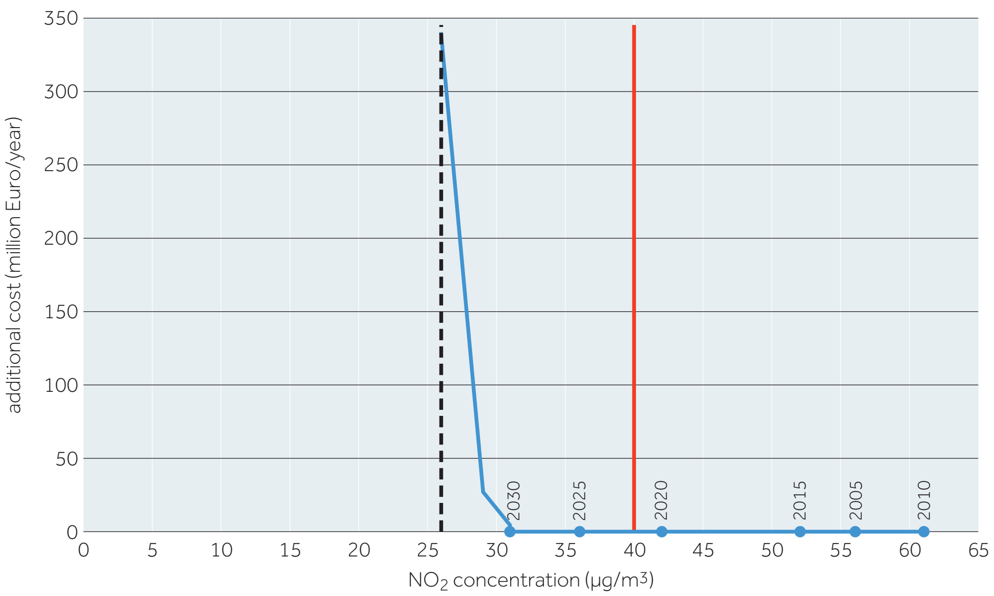
Predicted concentrations are compared to the associated cost, under different optimised scenarios that assume the adoption of additional measures beyond the CLE scenario (2005–2030) and towards the MTFR scenario, following a 'gap closure' concept.[1]

optimised case (IIASA) — EU AQLV / WHO guideline value — TSAP #16 2030 MTFR — TSAP #16 CLE

a) France



b) Poland



[1] The optimised scenarios presented here do not take into account vehicle measures that are defined in GAINS. If these measures had been considered, the associated cost would be higher than that shown on Figure 8.

Conclusions

To inform the ongoing EU AAQ Directives fitness check and potential revision process, Concawe conducted a study to highlight the importance of following a two-step process of firstly assessing the environmental and human health risks presented by concentrations of air pollutants (risk assessment step) and secondly, assessing how these risks may be managed (risk management step) when binding AQLVs are set.

The study assesses the practicability of achieving compliance with the current EU AQLVs for $PM_{2.5}$ and NO_2, as well as lower limit values, under some potential emission reduction scenarios. Results for two countries (Poland and France) are used as representative examples, and show that:

- The current emissions legislation, as described under the CLE scenario, will be effective in reducing $PM_{2.5}$ and NO_2 concentrations from 2025 onwards. However, full compliance with the existing EU AQLVs will not necessarily be achieved in all EU countries. Importantly, even ambitious non-technical measures taken to address what are widely seen as the root causes of non-compliance are not in themselves entirely effective.
- Reductions beyond the already legislated emission reduction measures, and towards MTFR, will require a substantial economic investment for only a small impact on the reduction of PM and NO_2 concentrations and the subsequent compliance improvement. In some cases (e.g. Poland for $PM_{2.5}$ and France for NO_2), full compliance with the current EU AQLV remains unachievable even if all MTFR measures are implemented.
- For $PM_{2.5}$, alternative non-technical emission reduction scenarios (not included in the IIASA GAINS model) such as the substitution of solid fuels with gas or liquid alternatives in the domestic sector, reduce concentrations significantly and improve compliance. The effects are particularly substantial in Eastern European Member States where coal is still widely used domestically. Measures targeting NH_3 emissions from agriculture are also predicted to offer further PM reductions, while the electrification of road transport is not expected to have a significant effect on PM levels, regardless of the vehicle categories or proportion of the vehicles substituted. The substitution of domestic solid fuel, however, is not necessarily enough to achieve full compliance with the current AQLVs everywhere in Europe; however, the reductions are significant enough to warrant an evaluation of the associated costs.
- For NO_2, road transport measures are predicted to lead to additional concentration reductions. However, even forcing the electrification of all vehicles on the road, which is not feasible in such a short time frame, would still fail to achieve compliance at some EU monitoring stations by 2030. Similarly, the full application of technical measures (MTFR scenario) will not achieve compliance everywhere.
- For both pollutants, the country variation is significant. In the examples shown, France has an issue with compliance for NO_2 but not $PM_{2.5}$, and Poland has an issue with $PM_{2.5}$ but not NO_2.
- A revision of the AAQ Directives that would adopt the WHO air quality guideline value of 10 $\mu g/m^3$ for $PM_{2.5}$ may result in widespread non-compliance in most European countries, regardless of the measures applied to control emissions.

It is extremely important that all consequences of changing the AQLVs embedded in the Air Quality Directive are considered from the perspective of implementation. Managing the risk of increasing challenges with non-compliance needs to be a priority for the review. It is clear that the application of further technical measures to address major sources of emissions has limited potential to affect concentrations, and that such measures have very high additional costs associated with them.

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Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 time frame

A summary of Concawe's '*CO_2 reduction technologies*' and '*Refinery 2050*' reports

This article summarises the results of two Concawe studies which address the potential for refineries to contribute to a future low-carbon economy. Full details of the studies are presented in Concawe reports 8/19 and 9/19, published in 2019.[2,3]

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Introduction

In December 2015, COP21 in Paris took an important step towards addressing the risks posed by climate change through an agreement to keep the global temperature increase 'well below 2˚C' and drive efforts to limit it even further to 1.5˚C. To achieve these goals, the European Union (EU) is exploring different mid-century scenarios leading to a low-carbon EU economy by 2050.

In line with the EU's low-emissions strategy, Concawe's cross-sectoral Low Carbon Pathways (LCP) programme is exploring opportunities and challenges presented by different low-carbon technologies and feedstocks that have the potential to achieve a significant reduction in carbon dioxide (CO_2) emissions associated with both the manufacture and use of refined products in Europe over the 2030–2050 time frame.

Within this context, two new Concawe refining-related reports have recently been published, which focus on the transition of the European refining industry and products towards a low-CO_2 economy, and explore the technical implications of the deployment of 'Vision 2050'[1] across the EU refining system and its contribution to EU decarbonisation goals:

1) *CO_2 reduction technologies. Opportunities within the EU refining system (2030/2050)*[2] (Step 1)
   This report focuses on the potential of different low-CO_2 technologies and operational measures to achieve a reduction in CO_2 emissions intensity within the refinery site, towards the 2030 and 2050 time horizons.
2) *Refinery 2050: Conceptual Assessment*[3] (Step 2)
   Building on Step 1, this analysis expands the scope by exploring the potential introduction and processing of low fossil carbon feedstocks in European refineries with the objective of producing lower fossil carbon fuels in a 2050 demand scenario. Through some initial selected examples of key low fossil carbon technologies, it investigates the potential synergies with the existing assets as crude oil is progressively replaced, and the implications in terms of feedstock supply, key processing requirements such as hydrogen and electricity, and CO_2 emissions intensity both at the refinery and end product levels.

Articulated around refining technologies, these two key reports aim to answer some key questions, such as:

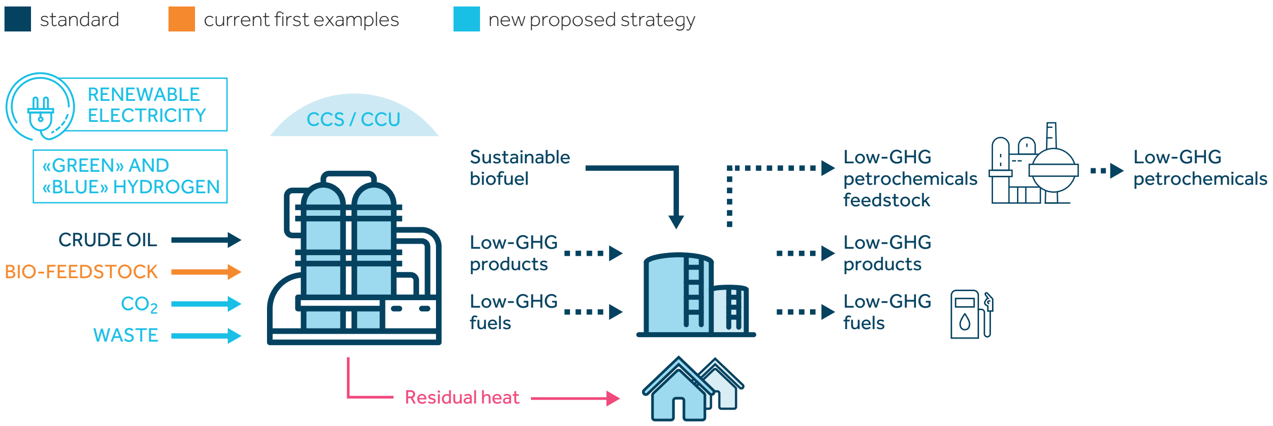
- Can the EU refining industry effectively contribute to a low-CO_2 economy?
- What kind of technologies can play a role in that future, and what is their current level of development?
- What framework conditions would be required to make this happen?

[1] https://www.fuelseurope.eu/vision-2050/
[2] https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf
[3] https://www.concawe.eu/wp-content/uploads/Rpt_19-9.pdf

Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 time frame

Figure 1: Conceptual overview of the refinery of the future—the refinery is an energy hub within an industrial cluster

Source: Vision 2050



This article is intended to serve as a brief summary of both reports, guiding the reader through the same path walked by Concawe in its aims to understand the future role for the refining industry. It highlights the main takeaways of the reports, and aims to provide the reader with an appetite to gather more information by reading the full texts of the reports.

Figure 2 (below) and Table 1 on page 31 illustrate the two-step approach and the complementary nature of the two refinery-related reports mentioned above.

Figure 2: The two-step approach of the two refinery-related Concawe LCP reports (Step 3 in elaboration)

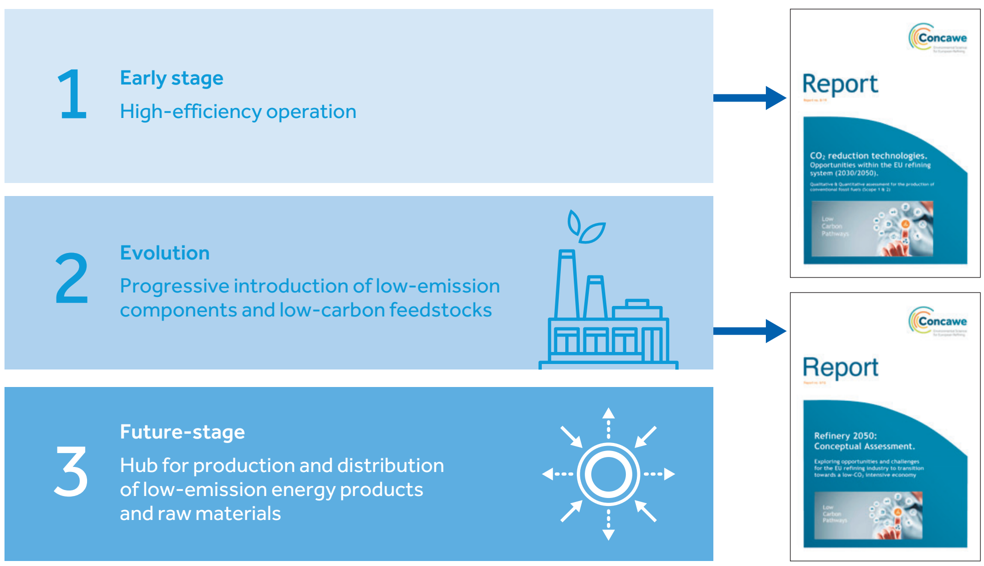


Table 1: The two-step approach and the complementary nature of the two refinery-related Concawe LCP reports

	Step 1 '*CO_2 reduction technologies*' report (Concawe report no. 8/19)	**Step 2** '*Refinery 2050*' report (Concawe report no. 9/19)
Scope (CO_2 savings)	Refinery battery limits (Scope 1 and 2 — direct and indirect emissions)	Expand scope from refinery battery limits to the final use of products (Scope 1 and 2, and a look into Scope 3).
Technologies	Technologies to reduce CO_2 emissions across the EU refining system.	Technologies which reduce the CO_2 emissions of the refinery (identified in Step 1) + low fossil carbon feedstock (co-located or co-processed within the refinery).
Time frame	What could be realistically achievable by 2030. A look into wide deployment towards 2050.	A look into the 2050 time frame (potential progressive deployment from 2030 onwards).
Demand	Based on a 2030 demand scenario (WoodMac, 2018).[a] No change in the activity level of the sector/product yields from 2030 onwards.	Exploring different routes and 2050 demand scenarios impacting both the activity level of the sector and product yields.
Feedstock	Crude oil	Crude oil progressively replaced by low fossil carbon feedstocks (e.g. biofeedstocks + e-fuel liquids).

[a] WoodMac, 2018 — data provided to Concawe

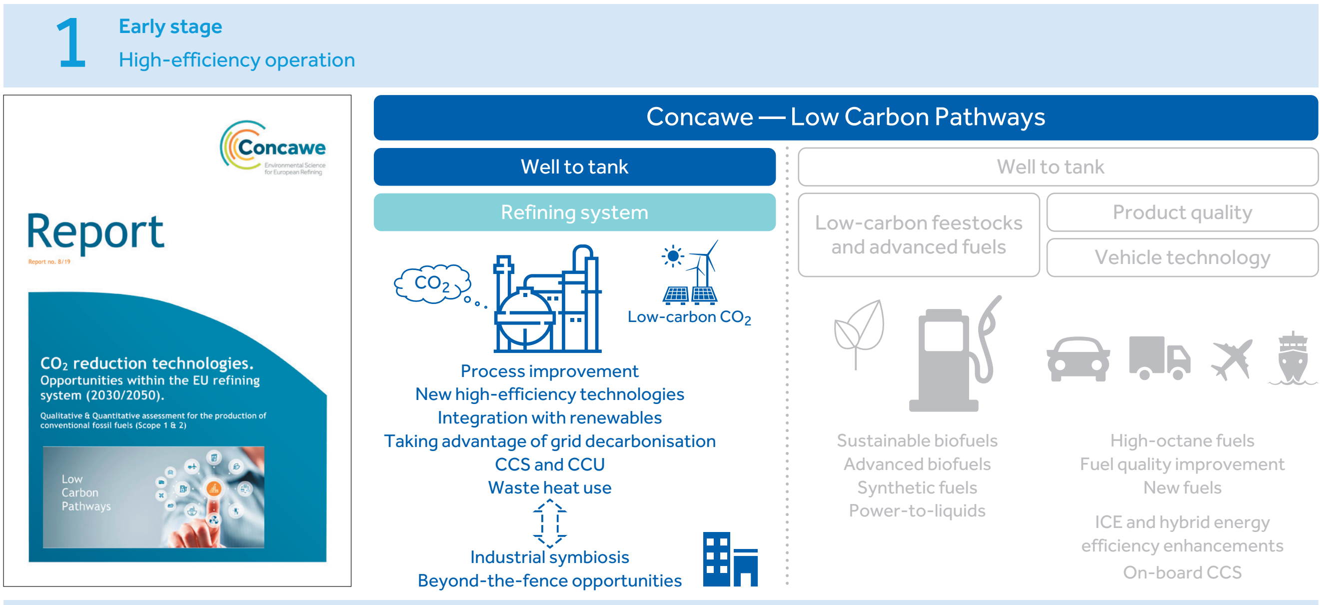
It is important to note that none of the Concawe LCP-related work is intended to be a roadmap for the whole EU refining and transport industries. Different factors coupled with local and structural constraints will determine individual companies' preferred routes to contribute to EU goals to mitigate climate change.

CO_2 reduction technologies. Opportunities within the EU refining system (2030/2050) (Step 1)

Overview: what is this report about?

This document demonstrates that the effective deployment of different technologies has the potential to achieve a significant reduction in CO_2 emissions in the EU refining sector. The starting point is the definition of a demand scenario for refinery products in 2030, followed by the modelling of different technologies and a plausible deployment rate to reduce CO_2 emissions produced at the site during the manufacturing process towards the 2030 and 2050 time horizons.

Figure 3: An overview of CO_2 reduction technologies (Step 1)



When looking at the emerging opportunities for reducing CO_2 emissions at the refinery site, different categories of opportunity become apparent:

- **Low-carbon energy carriers:** the gradual decarbonisation of the EU electricity grid or the natural gas network will offer new ways to integrate low-carbon electricity and gas into the production system.
- **Process efficiency** technologies introduced at the industrial sites can minimise energy consumption and, therefore, avoid CO_2 emissions.
- **Carbon capture** technologies will enable refineries to make CO_2 available for either storage (CCS) or use (CCU), thereby integrating the EU refining system into a circular economy.

The study was undertaken with the purpose of:

- establishing the current status of EU refineries in terms of energy intensity and CO_2 emissions intensity, including a brief historical perspective and a comparison with the situation in other world regions; and
- exploring the future of low-CO_2 technologies when deployed across the whole EU refining system towards 2030 and further to 2050, and describing plausible CO_2 reduction pathways by addressing the following questions:
  - What can realistically be achieved through continued gradual improvement?
  - What is the potential for significant new technologies to enable step changes in CO_2 intensity?
  - What is the potential for hitherto untapped synergies with other sectors?
  - What could be the impact of changes to both the quality and quantity of demand for EU petroleum products?

External factors such as future energy prices, together with more effective R&D programmes, will play a role in boosting the deployment of the key technologies identified.

What is the basis of this study?

The starting point: the 2030 demand scenario

For the purposes of this study, the demand scenario (quality and quantity) was defined as a reference for the energy consumption and CO_2 emissions at the refinery site and at EU level.

The study therefore concentrated on the impact of energy efficiency and CO_2 intensity reduction measures. In this context, the starting point for the 2030 horizon was based on actual and detailed refinery data prorated until 2030, including factors such as product demand forecasts and known changes to the configuration of the EU refinery population (see Table 2 on page 34).

In Step 1, the focus is on what the CO_2 reduction technologies could deliver in the medium/long term. It is not the intention to reflect potential changes in demand onwards (from 2030 towards 2050), hence the demand scenario was fixed in that period. Different scenarios exploring the potential evolution of demand from 2030 to 2050, and investigating the role of alternative low-carbon feedstocks to oil, are assessed in Step 2 (the *'Refinery 2050'* report).

Table 2: Demand scenarios for 2030

	MT/YEAR		CHANGE FROM 2014 ACTUAL
	2014	**2030**	**2030**
All products	**536.6**	**464.5**	**-13%**
LPG	3.0	4.4	49%
Gasoline	82.5	50.9	-38%
Jet fuel	55.3	67.6	22%
Gas oils	268.2	233.4	-13%
Road diesel	191.0	165.7	-13%
Other diesels	17.7	16.0	-9%
Heating oil	52.6	40.9	-22%
Distillate marine fuel	7.0	10.8	55%
HFO	52.1	32.8	-37%
HFO inland 0.5% sulphur	15.9	6.2	-61%
HFO marine 0.5% sulphur	1.8	16.0	806%
HFO marine high sulphur	34.4	10.6	-69%
Bitumen	17.0	16.3	-4%
Lubricants	4.8	5.4	-13%
Petrochemicals	53.7	53.7	0%
Olefins	40.9	40.9	0%
Aromatics	12.8	12.8	0%

The modelling work: the integration of low-carbon technologies within the refineries

The 2030 refining system — including the reduction in demand and, therefore, in activity as well — was incorporated into a model which could then integrate all options in a systematic and consistent way, and arrive at a range of plausible CO_2-intensity reduction figures for the whole EU refining sector.

A bottom-up approach, looking at each of the 80 refineries currently in operation in the EU, would be impractical and would raise confidentiality issues. Instead, this study adopted a top-down approach, identifying which emission-reduction technologies and external opportunities might be available to EU refiners, and what impact they might have at the 2030 and 2050 horizons on the CO_2 intensity of the whole EU refining sector.

Relevant information was collected from literature and through consultations with experts from technology providers and Concawe member companies. In addition, different rates of deployment of technology, energy prices and the degree of decarbonisation of the electricity grid were explored for both the 2030 and 2050 time horizons.

The potential of each option was scrutinised in detail, taking into consideration:

- the underlying technologies, and their current and future state of development; and
- the internal and external factors (practical and financial) that might favour or constrain the adoption of such measures.

On this basis, the following assumptions were made to assess the impact of each option in a 'Median' case, and explore different sensitivities ('High' and 'Low' cases), for each of the 2030 and 2050 horizons:

- a specific set of energy and CO_2 prices, consistent with authoritative studies; and
- a maximum rate of uptake for certain options, consistent with the economic environment that we considered to be practical and plausible at the time horizon.

In addition, in the 2050 'Median' and 'High' cases, three alternative routes to achieve deep decarbonisation are considered, namely electric boilers and heaters (Max-e), electrolytic hydrogen (Max-h) and CCS (Max-c). Each of these options have different implications in terms of both the use of electricity and the technologies applied to achieve significant CO_2 reductions (these are also detailed in the report).

What can be learnt from the report?

Potential CO_2 savings

A variety of opportunities to implement CO_2 reduction technologies in the EU refining system are identified and clustered into three main categories as listed on page 32: low-carbon energy carriers; process efficiency; and CO_2 capture.

Figure 4 on page 36 shows the cumulative total emissions savings (i.e. including emissions from production of imported electricity and hydrogen production), the total electricity consumption and the associated refinery CAPEX for the main opportunities identified above. Each column shows the cumulated potential for a specific category for the 2030 horizon with increasing deployment towards the 2050 horizon.

Assuming that EU refining activity is maintained at the 2030 level,[4] when all options are exercised in the 'Median' case, the total EU refinery CO_2 emissions (direct and indirect[5]) can potentially be reduced by approximately 25% by 2030 and up to 60% by 2050 in the high-uptake cases compared to the 2030 reference case. It is worth noting that the 2030 reference case already considers a CO_2 reduction of approximately 30% (direct emissions) and 5% (direct and indirect) as compared to 2008.[6]

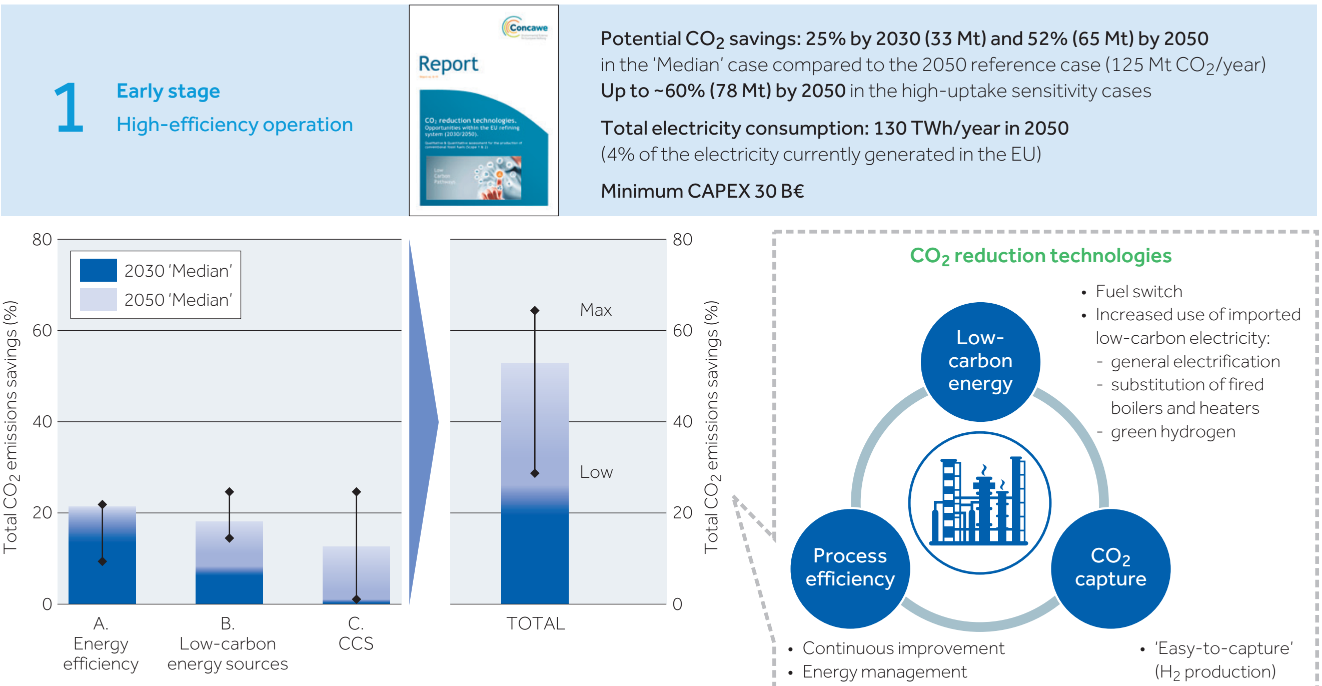
[4] Total CO_2 emissions in the 2030 reference case are ~125 Mt CO_2/year.

[5] Direct emissions considers emissions produced by the refinery. Indirect emissions includes emissions from sources not owned or directly controlled by the refinery but which are related to the activities of the refinery, such as emissions from off-site generation of electricity, steam or hydrogen.

[6] The smaller reduction in direct and indirect emissions compared to the reduction in direct emissions is due to the fossil component of the electricity grid and the fossil footprint associated with the biofeedstocks considered in 2030. Achieving complete renewability of feedstocks (using renewable energy in their production and transport) and importing 100% renewable electricity could potentially reduce these emissions.

This is equivalent to an annual total CO_2 emissions saving of 33 Mt (2030) to 65 Mt (2050) with the potential to increase this by up to 78 Mt by 2050 in the high-uptake sensitivity cases.

Figure 4: CO_2 reduction technologies and potential CO_2 savings



Note: electrification may account for up to ~23% of the CO_2 reduction in the 2050 'High' electrification sensitivity case. This incurs significant additional CAPEX outside the refinery not included in the scope of this assessment.

Investment level (CAPEX)

Figure 5 on page 37 shows that the CAPEX required to achieve these potential savings for the whole EU refining system is estimated at a minimum of ~30,000 M€ (2050 'Median' case). This estimated cost represents the generic cost of the different technologies and opportunities identified within the battery limits of the refinery. For example, it does not include fixed OPEX (operational costs), which would account for 25–40% of the total annual fixed costs, and would be highest for cases involving CO_2 capture. The actual cost of implementation would be determined by the specific conditions of each individual asset.

Abatement cost (€/t CO_2)

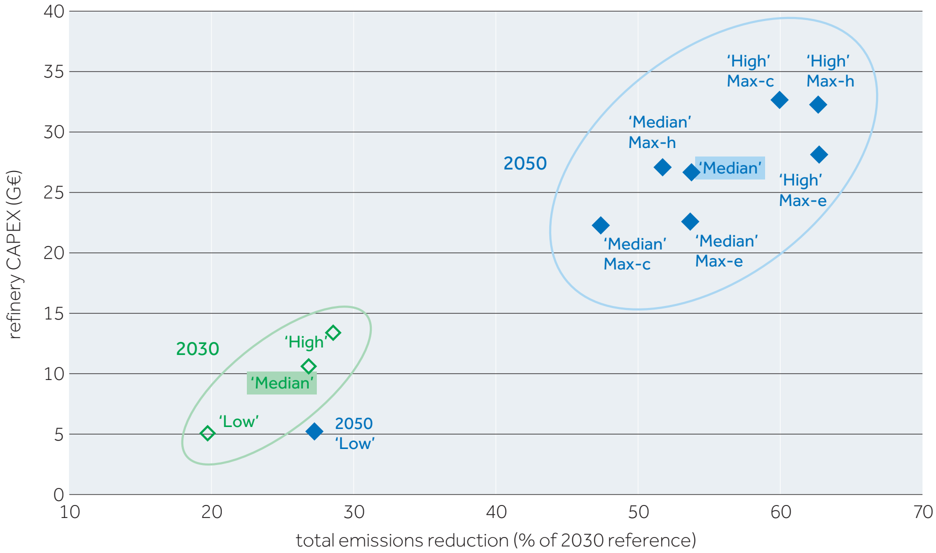
The abatement cost is a useful tool that enables the comparison of the cost of different options to reduce emissions by 1 tonne of CO_2. It is determined partly by the CAPEX (investment) and fixed OPEX required to implement a particular option. The abatement cost and the CO_2 CAPEX intensity are often used interchangeably (and commonly expressed in the same units, €/t CO_2, with no differentiation between them), but whereas the abatement cost provides a clear view of the real cost and is heavily affected by the energy prices (included in the OPEX), the CAPEX intensity is a fixed value which represents the level of investment needed.

Figure 5: Refinery CAPEX vs total emissions reduction, and a breakdown of the different low-carbon technologies

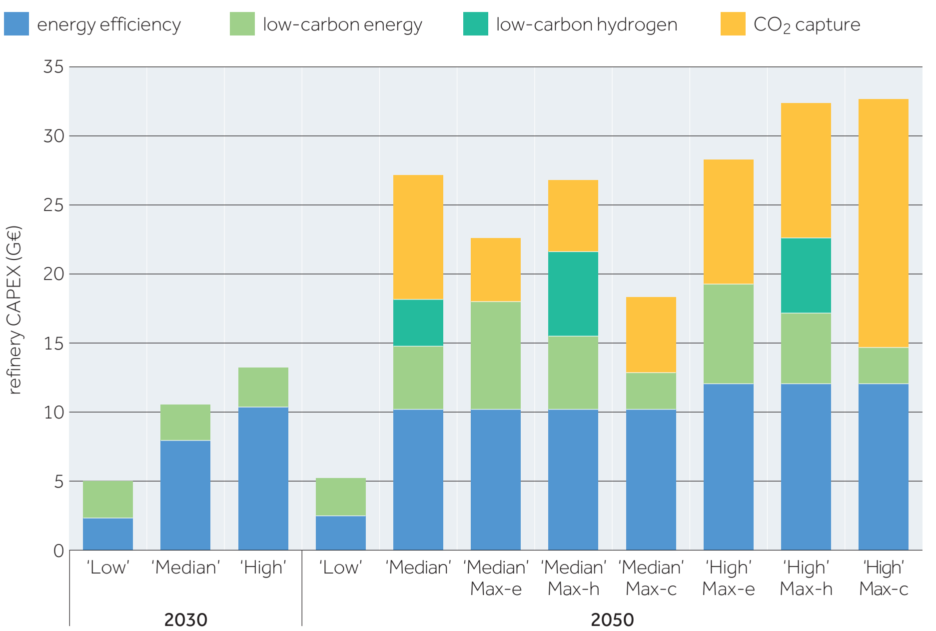
a) CAPEX vs emissions reduction

Max-h = Maximum hydrogen **Max-e** = Maximum electricity **Max-c** = Maximum CCS

Note: the 'Median' cases are highlighted as the main cases explored in the report



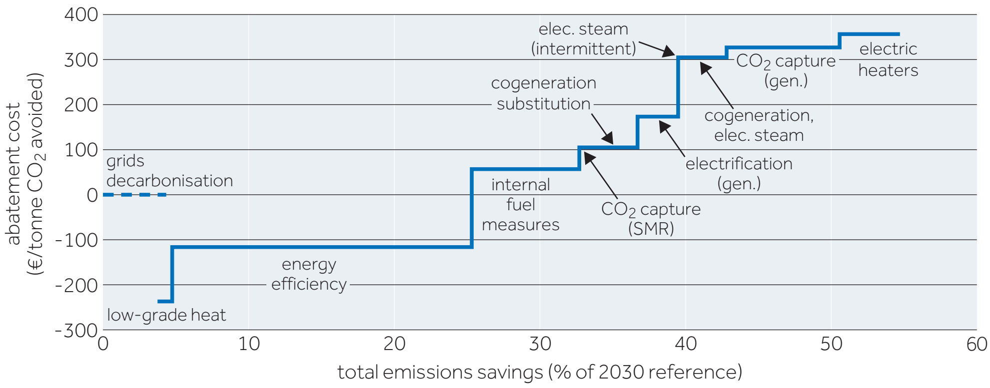
b) A breakdown of the low-carbon technologies



Therefore, there is no single CO_2 abatement cost per technology (Figure 6b). Figure 6a plots the abatement cost of each measure, as an example, ranked from low to high, versus the cumulative CO_2 emissions savings for the 2050 'Median' case.

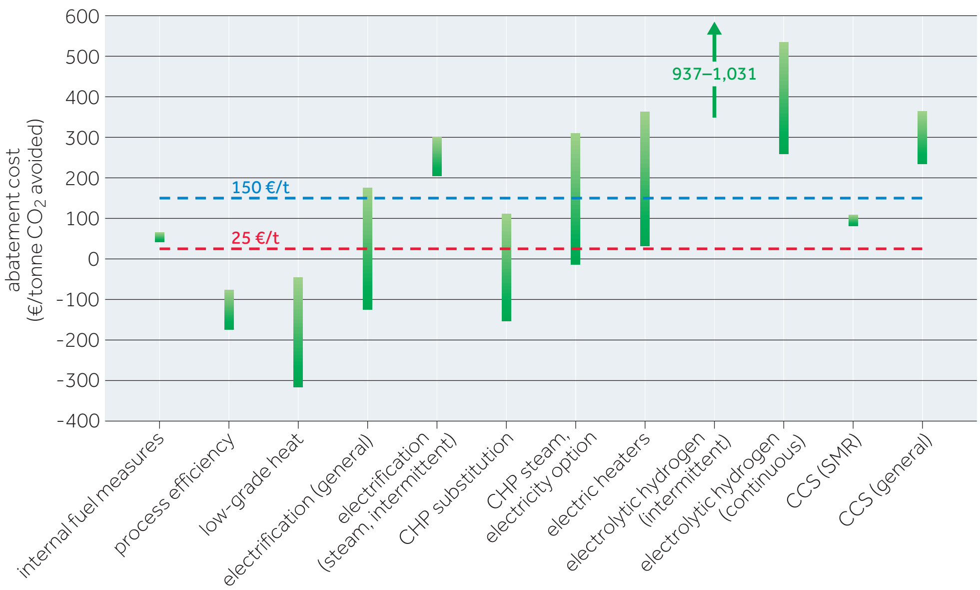
Figure 6: CO_2 abatement cost curve (2050 'Median' case), and example CO_2 abatement costs for different technologies

a) CO_2 abatement cost curve for the 2050 'Median' case



	2030			2050		
Case	**'Low'**	**'Median'**	**'High'**	**'Low'**	**'Median'**	**'High'**
Prices:						
Natural gas (€/GJ)	8	11	15	8	13	17
Electricity (€/MWh)	150	98	60	160	100	60
CO_2 (€/tonne)	25	35	75	25	90	150

b) Example CO_2 abatement cost per technology



Note: the horizontal dashed lines indicate the range of CO_2 prices considered in the different cases.

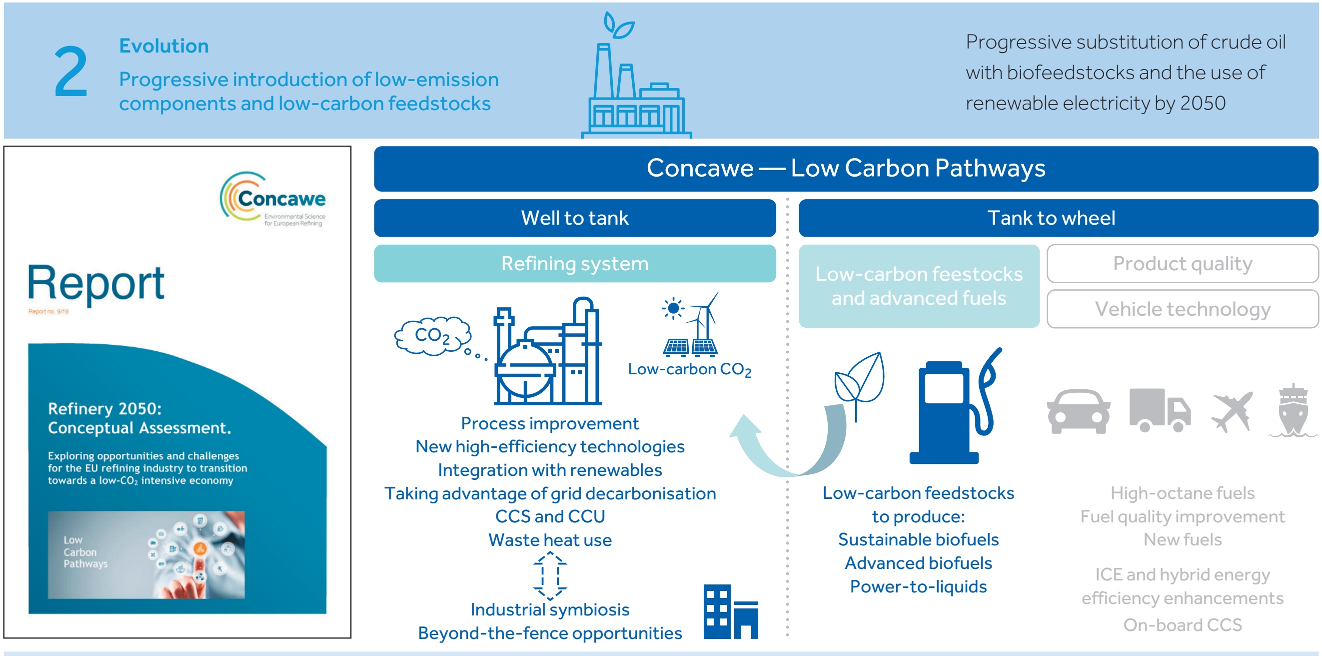
Internal measures and process efficiency improvements show close to zero or negative abatement costs under the energy price scenario considered. The historical profitability of the underlying investments, and the pay-back time threshold assumed for such projects, along with the discount rate (@ 15% capital charge) is used for consistency between all technologies shown on Figure 6.

Refinery 2050: Conceptual Assessment — alternative feedstocks (Step 2)

Overview: what is this report about?

As explained on page 29, this report builds on Step 1, and explores opportunities and challenges for the EU refining system to progressively integrate different low-carbon feedstocks in a mid-century demand scenario. Through a conceptual modelling exercise, some initial figures have been calculated and a range of potential implications have been identified in terms of utilisation and synergies with existing refinery assets, as well as additional electricity, hydrogen and feedstock requirements. It also provides the first estimate of the capital cost that would be required.

Figure 7: Overview of the ‘Refinery 2050’ concept (Step 2)



Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 time frame

What is the basis of this study?

The starting point: exploring the 2050 demand scenario

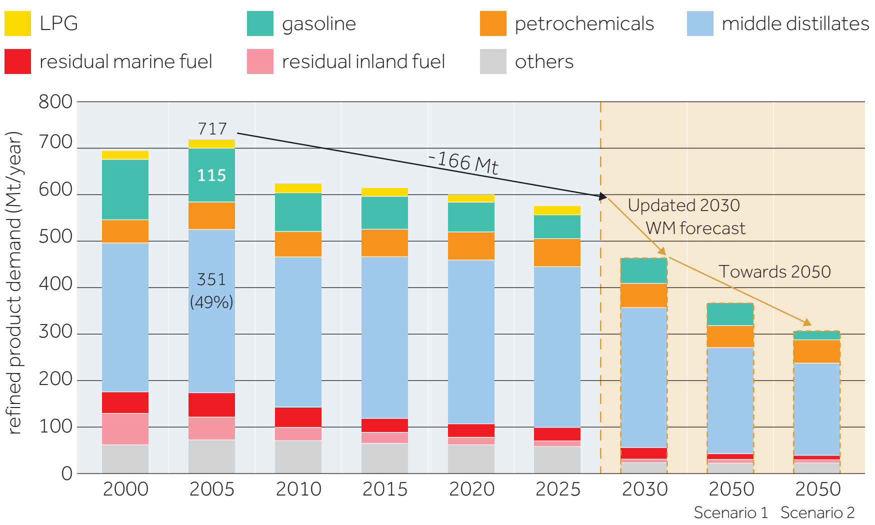
For the 2050 time frame, the main assumption for the demand scenarios is that the demand for most of the products that are currently produced by the refining industry will still be present in lower quantities due to competition with other technologies, and in sectors where no other alternatives are envisaged. In this context, the key question is how to ensure that the demand from the final customer (for end products or intermediate products supplied as feedstocks to other industries) is met in a low-CO_2 intensive manner.

In this context, two different demand scenarios have been explored with changes in the distribution of refining products. These scenarios:

- were initially inspired by the IEA scenarios (IEO, 2017)[7] and adapted to include Concawe's view on specific issues, including different levels of vehicle efficiency improvements and electrification of passenger cars, and reductions in the demand for heating oil and heavy fuel oil;
- define the basis for the modelling exercise which aims to explore the resilience of the refining scheme in the face of these changes as crude oil is progressively replaced by alternative low-carbon feedstocks; and
- provide the basis for the scale and range of both feedstocks and external requirements (e.g. electricity) at the EU level.

> The 2050 scenarios lead to a reduction in the refining throughput ranging from ~-20% (Scenario 1) to ~-35% (Scenario 2) versus the 2030 baseline.
> (Reduction in 2030 versus 2014 is -13%, as shown in Table 2 on page 34.)

Figure 8: Evolution of total demand for refined products in the EU-27+2 (including Norway and Switzerland)



Two different 2050 demand scenarios were explored, inspired by the IEA scenarios (IEA, 2017),[7] and adapted to include Concawe's view, for example:

- energy efficiency across all means of transport;
- a deep reduction in the demand for road diesel and gasoline due to penetration of alternative powertrains; and
- a reduction in marine fuel demand and a shift to middle distillates linked to the 0.5% sulphur limit.

Both scenarios lead to a reduction in refining throughput, ranging from -20% (Scenario 1) to -35% (Scenario 2) vs 2030.

Note: Scenario 2 was used as the main reference in the study.

[7] IEA (2017). *World Energy Outlook 2017:* 'New Policies Scenario' and 'Sustainable Development Scenario'. International Energy Agency.

Scenario 2 is used as the main reference in the study as an ambitious long-term scenario in terms of greenhouse gas (GHG) reduction.

The modelling work: the replacement of oil by low-carbon alternative feedstocks (an example of potential routes)

The modelling exercise explores fossil fuel cases as well as examples of the deployment of the low fossil carbon feedstocks through two different cases:

a) a limited case, where the intake of alternative feedstocks in the notional refinery is limited to the equivalent of 1 Mt/year liquid products; and
b) a maximum case, where alternative feedstocks provide the bulk of the intake (up to ~81% of crude oil replacement), the residual crude oil intake being determined by the need to satisfy the demand for bitumen.

The key basis for the modelling exercise is as follows:

- The modelling exercise is based on a Concawe-based refinery simulation tool (RafXL) calibrated against 2008 data.
- An average mid-range refinery was simulated (160,000 bbl/day of crude oil intake), consistent with the European average refinery configuration. This is a hypothetical refinery used for illustration and is not intended to represent a 'typical' refinery but to serve as the basis for a refining site being able to produce the required demand.
- Energy efficiency improvement rates of 19% and 22% in 2030 and 2050, respectively (from the 2008 reference), broadly representing the average between the 'Median' and 'High' cases detailed in the '*CO_2 reduction technologies*' report discussed on pages 32–39.
- Carbon capture (and storage) applied in selected cases. Waste heat from Fischer-Tropsch (FT) synthesis provided up to 80% of the capture energy demand.
- For alternative low fossil carbon feedstocks product yields, utilities requirements and basic product properties were derived from literature data.
- For each case, the capacity of the various process plants was adjusted (allowing extra new capacity where required) to best match the demand for all major products.
- Pathway scalability has been considered at two-levels, i.e. at an individual production facility and at the EU refining industry level.

What can be learnt from the report?

Low-carbon feedstocks: description and product yields for selected examples

This study investigates the potential for substantial replacement of crude oil with three main categories of selected low fossil carbon feedstocks (lipids, lignocellulosic biomass and e-fuels), each with different processing pathways (and associated yields), i.e.:

1) lipids hydrotreatment;
2) lignocellulosic biomass (e.g. wood):
    - gasification of lignocellulosic biomass, followed by Fischer-Tropsch synthesis and hydrocracking;
    - hydrotreatment/hydrocracking of pyrolysis or hydrothermal liquefaction oils made from lignocellulosic/woody biomass; and
3) e-fuels production from the conversion of captured CO_2 and electrolytic hydrogen into syngas by the reverse-water gas shift reaction, and then into hydrocarbons by Fischer-Tropsch synthesis with subsequent hydrocracking to produce fuels with a suitable boiling range.

A summary of the selected pathways explored in the report, and synergies with existing assets, is presented in Table 3.

Table 3: Summary of selected pathways explored in the report, and synergies with existing assets

		LIGNOCELLULOSIC BIOMASS		
	LIPIDS	GASIFICATION AND FISCHER TROPSCH ROUTE	PYROLYSIS ROUTE	E-FUELS
Illustrative pathway	Commercial lipid hydrotreatment has recently become well-established with a few stand-alone operations of up to 1 million tonnes/year.	Biomass-to-liquids (BTL). Gasification of woody biomass, followed by Fischer-Tropsch (FT) synthesis and hydrocracking.	Fast-pyrolysis or hydro-thermal liquefaction of lignocellulosic biomass or wastes, followed by hydrotreating to remove oxygen.	E-fuel from FT synthesis/hydrocracking of syngas derived from CO_2 capture + electrolytic H_2 using renewable electricity.
Product	Primarily paraffinic diesel and jet fuel.	Primarily paraffinic diesel and jet fuel, possibly with co-products such as chemical naphtha or wax.	Mix of biogasoline and biodiesel (relatively aromatic).	Primarily paraffinic diesel and jet fuel, possibly with co-products such as chemical naphtha or wax.
Feedstock	Typical feeds today: vegetable oil, animal fats or cooking oil; future expansion likely to rely on microbial/algal oils.	Lignocellulosic biomass including wood and residues from forestry, waste wood from industry, agricultural residues (straw and stover) and energy-crops. Potentially, municipal waste as well.		Captured CO_2 and renewable electricity.

Table 3 continues on next page ...

Table 3 (continued): Summary of selected pathways explored in the report, and synergies with existing assets

	LIPIDS	LIGNOCELLULOSIC BIOMASS		E-FUELS
		GASIFICATION AND FISCHER TROPSCH ROUTE	PYROLYSIS ROUTE	
Synergy with refining assets	**Very high** Lipid co-processing with fossil gas oil (5% up to 30% in suitable units with technology stretch). Potential for hydroprocessing refinery units to be adapted as dedicated lipids hydrotreater units (100%). Simplification by integration with refinery utilities, especially H_2 and LPG handling (significant capital saving).	**Moderate** New gasification/FT system; raw FT product is converted to fuel by co-processing in the refinery hydrocracker or by transformation of refinery unit to 100% biofeed. Integration with refinery utilities, especially power and LPG handling.	**Significant** Pyrolysis oil made 'in-field' simplifies biomass logistics. Pyrolysis oil is deoxygenated/upgraded to fuels by co-processing in the refinery unit. Raw oil may need treatment in a new stabiliser. Potential for unit transformation to 100% biofeed. Integration with utilities, especially H_2 (from co-processing to dedicated units).	**Moderate** New electrolysers and FT system. Raw FT product is converted to fuel by co-processing in the refinery hydrocracker or by transformation of the refinery unit to 100% biofeed. Refinery can use its own CO_2 emissions as feed for integrated e-fuel plants.
Technology and supply-chain readiness	Existing conversion technology and conventional supply chain. Future expansion requires development of new algae technology and the establishment of a significant new agricultural industry.	Conversion technologies have been commercialised separately in other sectors (power, natural gas) but have not been demonstrated at scale as an integrated process. A few forestry supply chains exist at >1 Mt/year scale, but significant replication would be needed.	Pyrolysis technologies have been demonstrated in a few small commercial operations, mainly in the heat/power sector. Upgrading to transport fuel is still at the developmental scale; refinery trials have been inconclusive. A few forestry/waste supply chains have been established (power sector), but would need significant replication.	Conversion technologies have been commercialised separately in other sectors (power, natural gas) but at very different scales. Integrated process still at pilot-scale. Potential for CO_2 utilisation at sites without CO_2 storage options or logistics.
External requirements	**High** (Sustainable feedstock availability)	**Very high** (Low-carbon electricity)		

Two series of cases were modelled in the study:

1. Limited low fossil carbon feedstock cases

In the first series of cases, after decreasing the throughput of the notional/average refinery to meet the 2050 demand scenario, the remaining crude oil intake was reduced by just under a quarter. The shortfall (about 1 Mt/year) was provided by one of the alternative feedstocks under consideration.

Table 4: A summary of the limited low fossil carbon feedstock cases (2050, average refinery)

KT/YEAR	FOSSIL CASE (2050) 50/2 FOS[a]	LIPIDS ROUTE (L1)	BIOMASS/FT ROUTE (BFT1[b])	BIOMASS/HTL (PYROLYSIS) ROUTE (BPY1)	E-FUELS ROUTE (FOE1)
Crude intake	4,300	3,280	3,280	3,280	3,300
Crude replacement (%)		24%	24%	24%	23%
Lipids	0	1,000	-	-	-
Biomass	0	-	4,250	2,250	
HT oil				970	
CO_2 capture					3,166
E-fuels	0	-	-	-	1,020
Hydrogen production	29.8	60	21	82	464
Electricity imports (GWh/year)	2,414	3,344	-1,536[c]	4,545	22,739
Direct fossil CO_2 emissions per refinery (fossil from site) (% reduction versus 2050 fossil case)	-	-54%	x 1.8[b]	-31%	-92%
Direct fossil CO_2 emissions EU-wide (fossil from site) (Mt/year)	42	18	76	28	4[d]

[a] 50/2 FOS relates to the 2050 demand scenario 2 assuming the 2050 level of energy efficiency with CO_2 emissions reduction through limited electrification, and no electrolytic hydrogen and CO_2 capture.

[b] The biomass FT (BFT1) route could increase the direct fossil emissions versus the base fossil case due to the partially fossil footprint associated with the biofeedstocks. Achieving complete renewability of feedstocks (using renewable energy in the production and transport) and importing 100% renewable electricity could potentially reduce these emissions.

[c] Due to the biomass gasification process and its associated surplus of heat, the refinery will end up exporting electricity.

[d] The EU electricity mix remaining fossil component has been assumed for the e-fuel production to be 40 t CO_2/GWh by 2050. Ensuring access to fully renewable electricity would have the potential to reduce the CO_2 emissions even further.

2. Maximum low fossil carbon feedstock cases

A second series of cases illustrated a hypothetical extreme situation where alternative feedstocks provided the bulk of the intake, the residual crude oil intake being determined by the need to satisfy the demand for bitumen.

Table 5: A summary of the maximum low fossil carbon feedstock cases (2050, average refinery)

KT/YEAR	LIPIDS + BIOMASS (LB)	LIPIDS + BIOMASS + CCS (LB-c)	BIOMASS + BIOMASS + E-FUELS (LBE)	BIOMASS + LIPIDS + E-FUELS (LBPE) [a]
Crude intake	810	810	810	810
Crude replacement (%)	81%	81%	81%	81%
Lipids	2,910	2,910	2,150	2,410
Biomass	3,810	3,810	2,800	3,640
HT oil				784
CO_2 capture			2,729	459
E-fuels			879	148
Hydrogen production	84.6		448.3	181.3
Electricity imports (GWh/year)	149	1,764	19,977	6,051
Direct fossil CO_2 emissions per refinery (fossil from site) (% reduction versus 2050 fossil case)	x 1.3 [b]	-200 % [c]	-70%	-30%
Direct fossil CO_2 emissions EU-wide (fossil from site) (Mt/year)	56	-90	13	29

[a] As LBE but limited e-fuels (16% capture) and with biomass 50/50 FT and pyrolysis oil (HTL process).

[b] The Lipids + Biomass (LB) route could increase the direct fossil emissions versus the base fossil case due to the partially fossil footprint associated with the biofeedstocks. Achieving complete renewability of feedstocks (using renewable energy in the production and transport) and importing 100% renewable electricity could potentially reduce these emissions.

[c] Negative emissions considered due to the CCS + biomass technologies coupling.

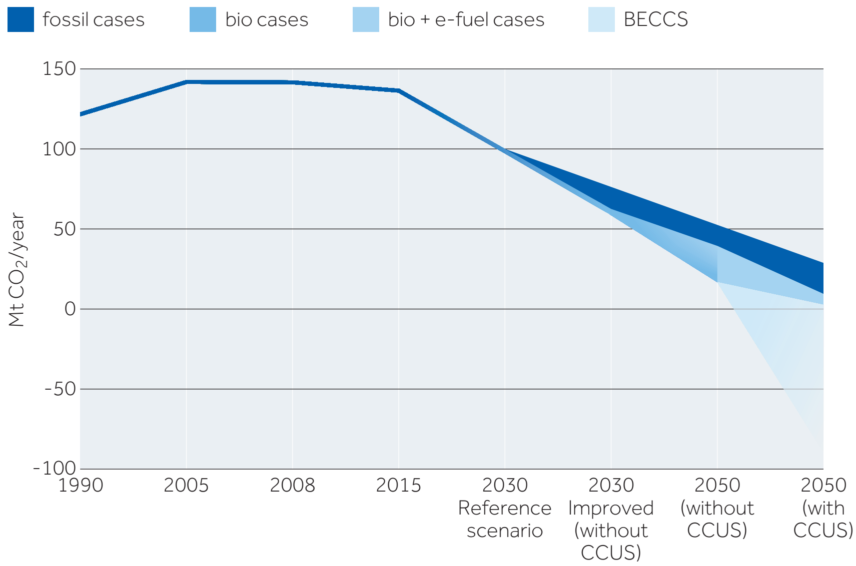
Potential CO_2 savings, electricity and hydrogen consumption, and CAPEX

Figure 9 shows potential evolution of CO_2 emissions at EU refinery sites resulting from the combination of measures identified in the '*Refinery 2050*' report.

The figure illustrates that, compared to the 1990 level, the CO_2 emissions from EU refinery sites (hence EU-wide) could be reduced by between 50% and 90%. When CCS solutions are combined with biomass feedstocks in BECCS (bioenergy with carbon capture and storage) schemes, net negative emissions could be achieved (compatible with the European Commission's long-term strategy, *A Clean Planet for all* [7]).

It also shows the total electricity and hydrogen consumption EU-wide, and the estimated CAPEX for a notional refinery.

Figure 9: EU-wide CO_2 emissions at refinery sites (direct fossil emissions; results from the '*Refinery 2050*' report)



EU wide:

- Potential CO_2 savings range from **50−90%** vs 1990, **and 85%** vs the 2030 improved scenario.
  Pathways enable negative emissions through biomass + CCS.
- **Total electricity consumption ranges from 150−550 TWh/year in 2050.**
  Consumption increases by 5 to 18 times vs the 2030 improved scenario.
- **Total hydrogen consumption ranges from 7−15 Mtoe/year in 2050.**
  Consumption increases by 2 to 5 times vs the 2030 improved scenario.

For a notional refinery (160 kbbl/day):

- **Estimated CAPEX could range from 1−10 G€** for the limited penetration cases, **and from 6−15 G€** for the extreme cases.

Impact beyond the refining boundary limits—an example:

In extreme cases the fossil carbon intensity of the main fuels could be reduced by 60–80% (diesel).

Feedstocks to petrochemicals also benefit from the renewable carbon intake—in extreme cases, up to around 60% non-fossil carbon.

Notes on Figure 9:

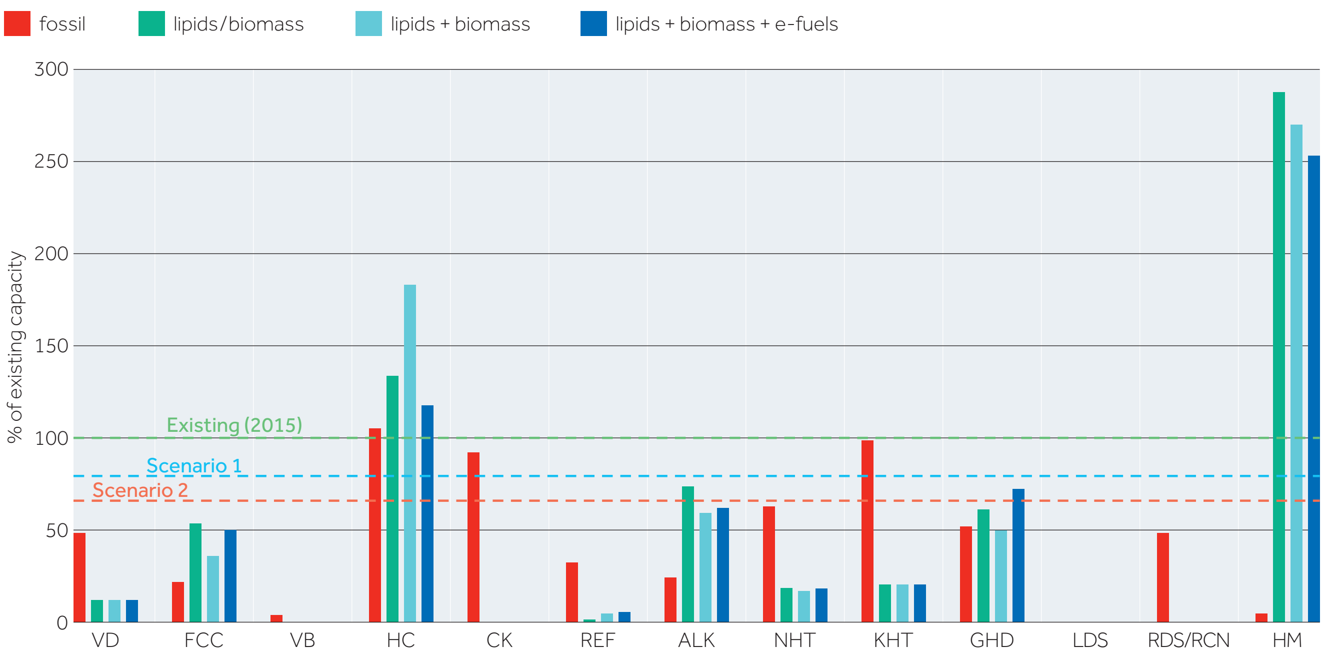
- The dark blue colour on Figure 9 relates to fossil cases where, once the demand reduction is taken into account, the upper and lower limits depend on the different penetration of CO_2 technologies identified in the '*CO_2 reduction technologies*' report (Step 1).
- The mid-blue colours relate to bio cases (lipids + biomass) and e-fuel cases.
- The very light blue relates to BECCS (bioenergy with carbon capture and storage); this technology is able to achieve negative emissions.

[7] https://ec.europa.eu/clima/policies/strategies/2050_en

Refinery utilisation level

Within this conceptual assessment, Concawe also looked at the potential utilisation levels of the existing process units within an average refinery when the selected alternative feedstocks are progressively processed instead of crude oil. The modelling work conducted shows that, due to the different composition and upgrade requirements necessary for the alternative feedstocks to meet the defined demand, some units could be operating well below their minimum operational rates. As a result, some rationalisation/downsizing may be required across the EU refining system to make these scenarios realistic from an operational point of view.

Figure 10: Refinery process plant utilisation



Process plants abbreviation key:

VD	vacuum distillation	REF	catalytic reforming	LDS	atmospheric residue desulphurisation
FCC	fluid catalytic cracking	ALK	alkylation	RDS/RCN	vacuum residue desulphurisation/conversion
VB	visbreaking	NHT	naphtha hydrotreating	HM	hydrogen manufacturing
HC	hydrocracking	KHT	kerosene hydrotreating		
CK	coking	GHD	gas oil hydrodesulphurisation		

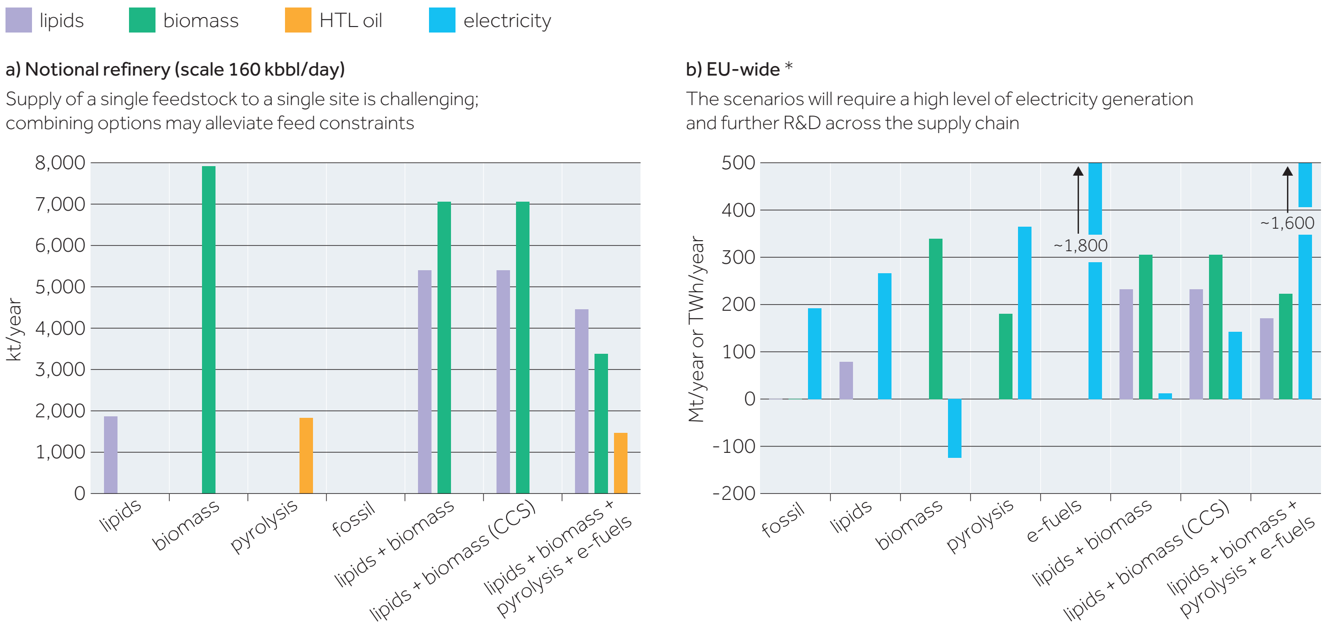
Generally speaking, the selected examples involve maximizing the hydrocracking and middle distillate hydrotreating routes, meaning that more capacity would be required than that which is currently defined for the average refinery. Consequently, the hydrogen requirements for processing these feedstocks also increases, and more hydrogen capacity would therefore also be required. On the other hand, the activity levels of some of the other units which usually operate at high levels of activity with current fossil crude oil—such as the coking unit—would not be minimised when fossil oil is largely replaced.

Furthermore, it is important to highlight that this first assessment is not intended to represent the future utilisation of all refineries in Europe; rather, its aim is to help us explore some initial examples of how alternative pathways can be combined in an average refinery, and assess the impacts that may occur in an average asset. Different refineries with different configurations may adopt a different combination of one or more of the pathways explored, among others, depending on factors such as their specific schemes or the proximity to a specific feedstock.

Alternative feedstock supply requirement

When looking at the feedstock requirements and other utilities (such as electricity), the different cases explored show different profiles—see Figure 11.

Figure 11: Alternative feedstock supply requirement



* Note: as a reference, net electricity generation in the EU-28 was ~3,100 TWh in 2016 (Source: Eurostat)

The study predicts that, in all cases, the scenarios will require high levels of renewable electricity (up to 1,800 TWh/year at the EU level) and an increase in the low-carbon feedstocks availability (up to 200 Mt/year for lipids and 300 Mt/year for wood at the EU level).

A literature review on the maximum potential availability and demand for low-carbon feedstocks in Europe in the 2020–2050 time frame was published in the Concawe *Review*, Vol. 27, No. 2.[8] According to references such as DG R&I and Ecorys (2017),[9] the maximum sustainable low-carbon feedstock availability in Europe would be 500–600 Mt/year by 2030 (and up to 700 Mt/year in the 2050 'High' R&D scenario).

[8] https://www.concawe.eu/wp-content/uploads/Concawe-Review-27-2-web-resolution-2.pdf

[9] https://op.europa.eu/en/publication-detail/-/publication/448fdae2-00bc-11e8-b8f5-01aa75ed71a1

Research and development framework

When the technology readiness level (TRL) of each of the different technologies explored is assessed (see Figures 12 and 13), it can be seen that the different opportunities identified in these studies are at different stages of development. Therefore, to reduce the CO_2 intensity of refinery sites and products, and for the identified potential to become a reality at reasonable cost for each time horizon (2030 and 2050), some key enablers would be required:

- Some technologies are ready or almost ready for deployment, and the industry is taking steps in this regard (e.g. CCS, hydrotreating vegetable oils).
- Further technological development across the whole value chain is key to increasing the availability and mobilisation of sustainable low-carbon feedstocks as key enablers to minimise CO_2 emissions at both the site and end-product levels.
- Boosting efforts in R&D/scaling-up of technologies common to different pathways, such as low-carbon hydrogen and CCS/CCU, are considered to be key building blocks for reaching deep decarbonisation levels.
- A number of key R&D challenges associated with the low-carbon feedstock technologies will need to be met; some of these identified in Table 6.
- Cross-sectoral and collaborative R&D efforts with stakeholders across the value chain (specially the supply chain) are expected to accelerate the development and scale-up of the key technologies.

Beyond this, refineries will need to attract the investment required to revamp existing plant, or build new plant and the required infrastructure to facilitate the integration of developing low-CO_2 technologies. A supporting regulatory framework and economic environment are envisaged to play a key role in this regard.

Table 6: Key R&D challenges for low-carbon alternative feedstocks

FEEDSTOCK	KEY R&D CHALLENGES
Lipid	• Alternative feedstocks development (e.g. waste, algae); biology still in early stages of R&D.
BTL	• Technology not yet commercially available. • How to ensure continuous operation when processing different feedstocks is still an issue. • Conversion efficiency/increasing resource availability are key factors. • Establishment of large lignocellulosic/residue supply chain in line with new plants start-up needed.
Pyrolysis	• Technology needs to be scaled up. • Processing of pyrolysis in refineries requires further R&D.
E-fuels	• Technology needs to be scaled up. • Efficiency improvements are required to reduce electricity requirement and improve CO_2 capture ratio → cost reduction.

Figure 12: Technology development—deployment status of various technologies (*'CO_2 reduction technologies'* report)

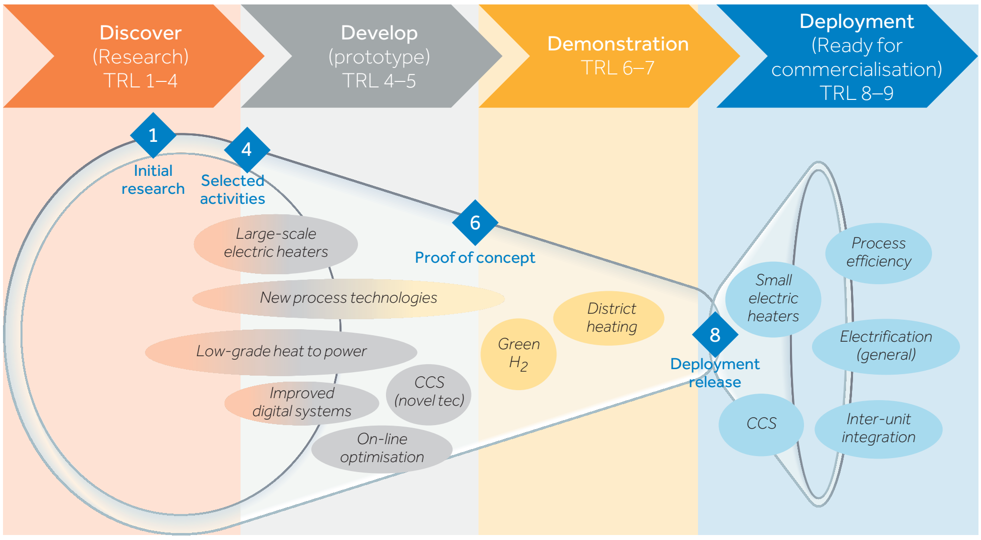
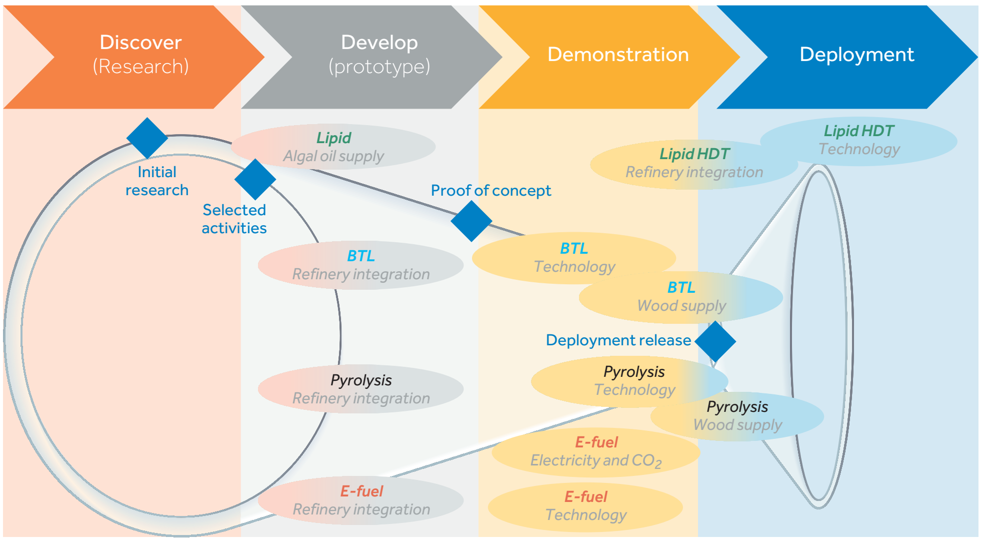


Figure 13: Technology readiness levels and key R&D challenges—alternative feedstocks (*'Refinery 2050'* report)



As shown in Figure 13, the TRL of most of the low-carbon alternative feedstock technologies is lower than the TRL of most of the CO_2 reduction technologies. Considerable efforts to boost R&D and scale up the development of low-carbon alternative feedstocks technologies are therefore required.

Concawe's main takeaways

Concawe's takeaways from the studies described in the two reports are summarised below.

- The EU Commission has recently published its long-term strategy (*A Clean Planet for all*), confirming Europe's commitment to take a lead in global climate action.
- All the scenarios assessed considered a decline in demand for fossil fuels towards 2050, which is either moderate or aggressive depending on the external sources consulted.
  - However, in all cases, there will be a remaining demand for liquid and other products that could be produced within the future vision and evolution of the EU's refining vision.
  - The Concawe studies assume a reduction in total demand of 13% in 2030 versus 2014, and from 20–35% by 2050 versus 2030, depending on the scenarios considered.
- The challenge for the refinery of the future has a double dimension — CO_2 reductions at the site, and the need for those reductions to be accompanied by technologies/feedstocks to reduce end-use emissions (i.e. from fuels and products).
- From a technical point of view, there are technologies at different stages of development that could help refineries to contribute to this long-term goal internationally. Examples include:
  - Delivering low-carbon fuels (selected examples modelled in these reports include biofuels, and e-fuels including H_2). Some of these routes—specially the e-fuels route—would only reach significant CO_2 savings if access to renewable electricity is ensured.
  - Alternative hydrogen production routes with lower-CO_2 intensity—these would become key enablers for future pathways.
  - Availability of large amounts of both renewable electricity and low-carbon feedstocks (including biomass).
  - The combination of different pathways may offer a way to alleviate the resource risk.
  - Increasing resource availability and mobilisation (supply chain), and technology scale-up/efficiency improvements are key to enabling the deployment of low-carbon technologies; greater levels of R&D will be required in these areas.
- The assessment is not intended to be a roadmap; multiple additional pathways/feedstocks could also be integrated within the EU refining system.
- The challenges go beyond the bio-industry/refining battery limits and, therefore, cross-sectoral collaboration will become even more crucial in the future.

Concawe's work on the cross-sectoral Low Carbon Pathways (LCP) programme will continue beyond the two reports discussed in this article, with more deep dives into some of the technologies already identified. This work will both expand and complement the scope of the previous reports by exploring additional low-carbon pathways that may follow. Readers are invited to visit the 'Low Carbon Pathways' area of Concawe's website for the latest information: https://www.concawe.eu/low-carbon-pathways/

Abbreviations and terms

AAQ	Ambient Air Quality
AQLV	Air Quality Limit Value
BDC	Bottom Dead Centre
BECCS	BioEnergy with Carbon Capture and Storage
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BTL	Biomass To Liquids
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CHP	Combined Heat and Power
CLE	Current Legislation
CO_2	Carbon Dioxide
CR	Compression Ratio
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EU	European Union
EUDC	Extra-Urban Drive Cycle
FT	Fischer Tropsch
GAINS	Greenhouse gas — Air pollution INteractions and Synergies
GHG	Greenhouse Gas
H_2	Hydrogen
HOP	High-Octane Petrol
HTL	HydroThermal Liquefaction
IAM	Integrated Assessment Model
ICE	Internal Combustion Engine
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
LCP	Low-Carbon Pathways
LDV	Light-Duty Vehicle
LPG	Liquefied Petroleum Gas
MON	Motor Octane Number
MTFR	Maximum Technically Feasible Reductions
NEDC	New European Drive Cycle
NH_3	Ammonia
NMVOC	Non-Methane Volatile Organic Compound
NO_2	Nitrogen Dioxide
NO_3	Nitrate/Agricultural Ammonia
NO_x	Nitrogen Oxides
OPEX	Operating Expenditure
PCD	Passenger Car Diesel
PCG	Passenger Car Gasoline
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter less than 2.5 µm
R&D	Research and Development
RDE	Real Driving Emissions
RON	Research Octane Number
SMR	Steam Methane Reforming
SNAP	Selected Nomenclature for sources of Air Pollution
SO_2	Sulphur Dioxide
TDC	Top Dead Centre
TRL	Technology Readiness Level
TSAP	Thematic Strategy on Air Pollution
UDC	Urban Drive Cycle
UK	United Kingdom
VCR	Variable Compression Ratio
WHO	World Health Organization
WLTC	Worldwide harmonized Light-duty Test Cycle

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4/20	Air emissions from the refining sector. Analysis of E-PRTR data 2007-2017
3/20	Aquatic toxicity of petroleum substances: Extending the validation of the biomimetic extraction (BE) method for use in hazard assessments
1/20	Odour management guidance for refineries

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